3. RADTRAN INPUT

The RADTRAN code [3-1, 3-2] calculates estimates of the risks associated with the transportation of radioactive materials, for example spent nuclear fuel. For a specific material, package, and route, the code develops estimates of a variety of consequences and risks for both incident-free transport and transport subject to accidents.

The RADTRAN code requires a very large quantity of data to describe the incident-free transportation of a radioactive material and also the accident scenarios and the radiological doses that might be received by population groups located along the shipment route. Selecting appropriate values for all the parameters used by the RADTRAN code to estimate transportation consequences and risks is a substantial undertaking. Selection of parameter values is further complicated by the fact that the casks and routes that will be used in the real spent fuel shipping campaigns are presently unknown. Fortunately, there is a large body of existing analyses that provide guidance on ranges of variables and their importance to the result. This knowledge base is significant in performing multiple analyses addressing a variety of conditions contained in this document. Experience allows the analyst to focus on identifying the variables that affect the results directly and getting their reasonable ranges correct while spending much less time (and computing resources) on less important parameters.

3.1 Fixed and Sampled Input Variables

For spent fuel shipments, many RADTRAN input variables can take on a wide range of real-world values (e.g., route lengths, wayside population densities, evacuation times). Fortunately, not all of these variables strongly influence predictions of the consequences and risks associated with the transportation of spent nuclear fuel. Spent fuel transportation risks are strongly influenced by a number of RADTRAN input variables [3-3, 3-4], some of which may take on a wide range of values in the real world. For these variables, construction of distributions and selection of values from these distributions by structured sampling methods offers an efficient way to assure coverage of the full range of each variable and also of the many possible combinations of the values of different variables that might be encountered in the real world.

RADTRAN input variables may be divided into two groups:

- those required for accident analysis, and
- those required for incident-free analysis.

Within each of these groups, RADTRAN input variables can be further divided into:

- variables that strongly affect incident-free or accident consequences or risks (More Important Variables)
- variables that do not strongly affect incident-free or accident consequences or risks (Less Important Variables)

Finally, the “More Important” RADTRAN variables can be divided into Source Term Variables (i.e., accident severity fractions and release fractions) and other “More Important” Variables.

The difference between More Important and Less Important Variables may be conceptually described as follows. Let R be incident-free dose or accident dose-risk, v_i be a RADTRAN input variable, and the fractional change in risk for a fractional change in the variable be

$$\frac{\Delta R}{R} = k_i \frac{\Delta v_i}{v_i}$$

Then, $k_i \approx 1.0$ for More Important Variables and $k_i << 1.0$ for Less Important Variables. Thus, for More Important Variables, a fractional change (e.g., a 10 percent increase) in the value of the variable produces about the same fractional change in risk (e.g., about a 10 percent increase or decrease). Conversely, for Less Important Variables, a fractional change in the value of the variable produces a much smaller fractional change in risk.

Central Estimates are Used for Less Important Variables

Although the values of nearly all RADTRAN input variables could be selected by sampling from distributions, constructing distributions for Less Important Variables is pointless because variation of the values of Less Important Variables influences consequence and risk results only slightly, if at all. Several RADTRAN input variables had been shown previously to have little influence on estimates of accident risk [3-5]. To verify the conclusions of this study specifically for spent fuel, single parameter sensitivity calculations were performed to investigate the effect of these variables on spent fuel transportation risks. Table 3.1 lists these variables, the trial values of each variable used in these sensitivity calculations, and the corresponding changes in total accident risk produced by the change. Table 3-1 shows that none of the five variables examined by these sensitivity calculations strongly affect risk. Therefore, for these variables, and all other variables known to have little effect on risk, central estimate values were used as input to all calculations performed for this study.

Table 3.1 Results of Sensitivity Calculations: Changes in Total Accident Risk Produced by Changes in the Values of Several Input Variables

Variable Name	Variable Definition	Base Case Value	Base Case Result	Sensitivity Case Value(s)	Sensitivity Case Result
BRATE	Breathing rate	3.3E-4	5.5E-06	1.6E-04	3.9E-6
BDF	Respirable aerosol fraction inside buildings	0.05	5.5E-06	5.0E-03 0.5	5.4E-06 6.8E-06
RPD	Ratio of pedestrian and resident population densities	6.0	5.5E-06	3.0 12.0	4.6E-06 7.4E-06
RU	Urban shielding factor	0.018	5.5E-06	0.01 0.18	5.5E-06 5.5E-06
CULVL	Clean-up level	0.20	5.5E-06	0.10 0.02	5.3E-06 4.8E-06

Central Estimates are Used for More Important Variables with Little Variation

Distributions need not be constructed for More Important Variables that have values that are fixed or that only vary over a narrow range. For example, some Important Variables have precisely defined values (e.g., radionuclide half lives) or have values that are fixed by regulations. Thus, central estimate values were also used for all More Important Variables that are invariant or that only vary over narrow ranges.

Central Estimates are Used for all Source Term Variables that can Vary Widely

RADTRAN source term magnitudes are specified by the product of the cask inventory, which can be precisely determined by ORIGEN calculations [3-6], and an accident release fraction. The probability of the release (the source term probability) is specified as the product of a severity fraction, which specifies the fraction of all possible accidents that lead to the given source term, and the probability that any accident occurs, which is calculated as the product of a route length and an accident rate. Because insufficient information exists from which to construct distributions for these important RADTRAN variables, as is described in Section 7, their variation was treated by constructing representative sets of truck and train accident release and severity fractions.

Distributions are Used for Other More Important Variables with Wide Value Ranges

Consequently, distributions were constructed only for other More Important Variables that have real-world values spanning a wide range (e.g., route lengths, accident rates, route wayside population densities, evacuation times). For these other More Important Variables, as is discussed below, distributions were constructed, usually by analysis of historic data for the variable, and then representative sets of values for each variable were selected from these distributions by structured Monte Carlo Sampling using Sandia National Laboratories' Latin Hypercube Sampling (LHS) computer code [3-7].

3.2 RADTRAN 1 and RADTRAN 5 Input Variables

Although the exposure and dose models implemented in RADTRAN 5 are the same as those implemented in RADTRAN 1, models for a variety of other phenomena have either been modified or added. In particular, RADTRAN 5 allows considerably greater flexibility in the way that transportation routes are modeled. The principal differences between these two versions of the RADTRAN code are summarized in Table 3.2.

Tables 3.3 and 3.4 respectively describe the incident-free and accident analysis input variables used in RADTRAN 1 and RADTRAN 5, and present the RADTRAN 1 and RADTRAN 5 names of each variable, the location (array name and position in the array) of the variable in RADTRAN 5, the sensitivity of RADTRAN output to each variable, the RADTRAN 1 and RADTRAN 5 value used for each variable, and clarifying comments or explanations. In Tables 3.3 and 3.4, the term "not in code" in the RADTRAN 1 or RADTRAN 5 variable name column indicates that no model implemented in the indicated version of the code uses this variable, and "Distribution" in

Table 3.2 Comparison of RADTRAN 1 and RADTRAN 5

	RADTRAN 1	RADTRAN 5
Route	Entire route modeled in three segments occurring in fixed proportions related to population density designations	Route may be divided into up to 60 user-defined segments (links)
Right-of-way width	Fixed for freeway, non-freeway, urban	User-defined
Population density	Rural, suburban, urban[a] – fixed densities	User-defined
Population density distribution along the route	Fraction of route that is rural = 0.9, suburban = 0.05, urban = 0.05	Population density can be defined for each link
Distribution of population along the route	Population is distributed in bands ½ mile (800 m.) wide on either side of the route	Band depth is user defined
Lane width	Fixed for rural, suburban, urban	User-defined
Vehicle speed	Fixed for rural, suburban, urban	User-defined for each link
Vehicle density (traffic count)	Fixed for rural, suburban, urban	User-defined for each link
Traffic distribution: rush hour, non-rush	Fixed fractions for rural, suburban, urban	Not needed, because speeds are user-defined
Traffic distribution by road type	Fixed fractions for rural, suburban, urban	Road type is user-defined
Stop time, distance from cargo, number of people	Fixed for rural, suburban, urban	User defined: each stop can be treated separately, like a link
Package shape factor	Not used directly	Used
Dose to close-in receptors	approximately $1/r^2$ dependence	approximately 1/r dependence
Dose to handlers	Treated like stop dose	Activity-specific parameters (distance, etc.) are user defined
Dose to crew	Fixed for various modes	User-defined
LCF/person rem (incident-free transportation)	2.57×10^{-4} LCF/person rem (accepted regulatory value in late 1970s) (disaggregated by target organ)	User-defined; current guidance is: 5×10^{-4} LCF/rem for public; 4×10^{-4} LCF/rem for workers
LCF (transportation accidents)	3.79×10^{-4} LCF/rem (disaggregated by target organ)	User-defined; current guidance is: 5×10^{-4} LCF/rem for public; 4×10^{-4} LCF/rem for workers
Accident frequencies	1974-75 national average data	User defined; 1988 state-by-state data are most recent available values
Accident severity categories	8 categories	Up to 30 categories available; number of categories and frequencies both user-defined
Loss of shielding accidents	Included	Included
Atmospheric dispersion meteorology	Fixed: national average meteorology	User-defined combination of stability classes
Ingestion model	Model similar to WASH-1400 [3-8]	COMIDA2 [3-9]

a. Rural, suburban, and urban areas are called low-density, medium-density, and high-density, respectively, in NUREG-0170.

Table 3.3 Comparison of RADTRAN 1 and RADTRAN 5 Input Variables that Affect Incident-Free Dose

Variable Definition	Variable Name		RADTRAN 5 Input Location	Sensitivity of Dose to Variable	Variable Value		Comments
	RADTRAN 1	RADTRAN 5	Array Name (position)		RADTRAN 1 (NUREG-0170)	RADTRAN 5 (this study)	
Maximum Dose Rate at 1 m from package surface (mrem/hr)	TIPKG	Package Dose Rate (DR)	PACKAGE (2nd)	Proportional	(not used)	Distribution (See Sect. 3.4.3.4)	For NUREG-0170, TIPKG was set to 1.0 which forced the package dose rate factor K to have a value of 1000 mrem-ft^2/hr.
Maximum dose rate at 1 m from vehicle surface (mrem/hr)	(not in code)	Vehicle Dose Rate	VEHICLE (3rd)	Proportional		Distribution (see package dose rate above)	The NUREG-0170 model did not treat the package and vehicle separately; for spent fuel, the package and vehicle dose rates were assumed to be the same.
Fraction of package dose rate that is gamma radiation	(not in code)	Gamma Fraction	PACKAGE (3rd)	Small	(1.0)	1.0	NUREG-0170 model assumed 100% gamma radiation, which is conservative.
Fraction of package dose rate that is neutron radiation	(not in code)	Neutron Fraction	PACKAGE (4th)	Small	(0.0)	0.0	NUREG-0170 model assumed 100% gamma radiation. Neutrons readily attenuated by concrete, humidity, etc.
Fraction of vehicle dose rate that is gamma radiation	(not in code)	Gamma Fraction	VEHICLE (4th)	Small	(1.0)	1.0	NUREG-0170 model assumed 100% gamma radiation, which is conservative.
Fraction of vehicle dose rate that is neutron radiation	(not in code)	Neutron Fraction	VEHICLE (5th)	Small	(0.0)	0.0	NUREG-0170 model assumed 100% gamma radiation. Neutrons readily attenuated by concrete, humidity, etc.
Characteristic package dimension (m)	PKGOE	Package Size	PACKAGE (5th)	Proportional	(not used)	5.2 for truck 4.8 for rail	Package dimension was not used by the NUREG-0170 spent fuel model. It was used offline to estimate the package dose rate factor (see TIPKG above) Values are for casks currently in service.
Characteristic vehicle dimension (m)	(not in code)	Vehicle Size	VEHICLE (6th)	Proportional		5.2 for truck 4.8 for rail	The NUREG-0170 model did not treat the package and vehicle separately.
Flag for exclusive use vs non-exclusive use	(not in code)	Exclusive Use	VEHICLE (modifies 2nd value in array)	N/A	Exclusive Use	Exclusive Use	
Number of shipments	SPY	Number of Shipments	VEHICLE (7th)	Proportional	For 1975, 254 for truck and 17 for rail.	1	NUREG-0170 examined results per year (1975); this study looks at results per shipment.

Table 3.3 Comparison of RADTRAN 1 and RADTRAN 5 Input Variables that Affect Incident-Free Dose (continued)

Variable Definition	Variable Name		RADTRAN 5 Input Location	Sensitivity of Dose to Variable	Variable Value		Comments
	RADTRAN 1	RADTRAN 5	Array Name (position)		RADTRAN 1 (NUREG-0170)	RADTRAN 5 (this study)	
Number of crew persons	1st value in DNORM array	Crew Size	VEHICLE (8th)	Proportional (crew dose only)	Truck: 2	Truck: 2	Because of distance from the cask rail car, both studies assume the train crew receives negligible in transit exposures.
Average distance of crew from nearest package surface (m)	3rd value in DNORM array	Crew Distance	VEHICLE (9th)	Proportional (crew dose only)	Truck: 3.0 m	Truck: 7.4 m	Dose calculated from package surface nearest crew rather than from source location at geometric center of package.
"Crew-view" package dimension (m)	(not in code)	Crew View	VEHICLE (11th)	Proportional		Truck: 2 m	See preceding comment on distance from package to crew.
Crew Modification Factor; accounts for shielding of crew, if any	(not in code)	Crew Modfac	VEHICLE (10th)		(1.0)	1.0	RADTRAN 5 allows cab shielding to be modeled; however, no shielding of crew was assumed in current calculations.
Number of packages per shipment	PKGSHP	Number of Packages	VEHICLE	Proportional	1	1	
Population Density at stop (persons/km^2)	POPZON	Population Density	STOP (3rd)	Proportional (stop dose only)	Rural: 6 Suburban: 719 Urban: 3861	Truck: 3E+04 Rail: Rural, 8; Suburban, 340	For RADTRAN 5, truck value based on empirical data; rail value reflects fact that, even in cities, rail yards are not surrounded by urban population density.
Minimum and Maximum radii of annular area around stopped vehicle	Fixed Value	Minimum Dist. Maximum Dist.	STOP (4th, 5th)	Proportional (stop dose only)	10 ft 2600 ft	Truck: 1, 10 m Rail: 30, 800 m Rail classification yard: 400, 800 m	In NUREG-0170 model, the 10 & 2600 ft values could not be changed. RADTRAN 5 values are for members of public; worker doses are computed separately.
Shielding factor	(not in code)	Shield Factor	STOP (6th)	Proportional (stop dose only)		1.0	Not in NUREG-0170 model; assumed to be 1.0 (i.e., everyone is outdoors). Set to 1.0 in this study for conservatism.
Stop time (hours)	8th, 9th, & 10th values in DNORM array	Stop Time	STOP (7th)	Proportional (stop dose only)	Truck Rail R: 1 24 S: 5 0 U: 2 0	Truck: Distribution (See Sect. 3.4.3.1) Rail: classification yard stops, 60 hr; all other rail stops, 0.033 hr/km.	In NUREG-0170 model, aggregate stop time for rural, suburban, and urban travel was entered. In RADTRAN 5, stop time can be aggregated or entered separately for each stop. Because trucks transporting spent fuel do not make stops to sleep. A correction factor to the results calculated using the truck stop time distribution is developed in Section 8.6.

Table 3.3 Comparison of RADTRAN 1 and RADTRAN 5 Input Variables that Affect Incident-Free Dose (continued)

Variable Definition	Variable Name: RADTRAN 1	Variable Name: RADTRAN 5	RADTRAN 5 Input Location: Array Name (position)	Sensitivity of Dose to Variable	Variable Value: RADTRAN 1 (NUREG-0170)	Variable Value: RADTRAN 5 (this study)	Comments
Storage time per shipment (hours)	DTSTOR		(not in code)	Small	Truck: 2 Rail: 4	N/A	RADTRAN 5 calculations assumed stops for storage didn't occur.
Population density of persons exposed during storage (mi^2)	PDSTOR		(not in code)	Small	Truck: 896 Rail: 25	N/A	RADTRAN 5 calculations assumed stops for storage didn't occur.
Minimum and maximum radii of annular area around storage location (ft)	(not in code)		(not in code)	Small	(5 ft, 1000 ft)	N/A	RADTRAN 5 calculations assumed stops for storage didn't occur. Storage exposure distance range was fixed in RADTRAN 1.
Link Length (km)	[FMPS]	Dist.	LINK (3rd)	Proportional	R: 2530×0.09 S: 2530×0.05 U: 2530×0.05	Distribution (See Sect. 3.4.1.2)	1975 Model used fixed route length (FMPS) and fixed fractions of rural, suburban, and urban travel as indicated.
Shipment velocity (mph) for calculation of incident-free results	V	Speed	LINK (4th)	Proportional	Truck: 55 mph Rail: R: 40 mph S: 25 mph U: 16 mph	Truck: 55 mph Rail: R: 40 mph S: 25 mph U: 16 mph	Truck value (55 mph) is used for interstates for all population densities. Applies to incident-free only; accident speeds not a direct RADTRAN input (see Chapter 7).
Persons per Vehicle	26th value in DNORM array	Persons per Veh	LINK (5th)	Proportional (on-link dose only)	2	Distribution (See Sect. 3.4.3.6)	
Link Population Density (persons/km2)	POPZON	Pop Den	LINK (6th)	Proportional (off-link dose only)	R: 6 S: 719 U: 3861	Distribution (See Sect. 3.4.1.4)	Values in NUREG-0170 Model were fixed.
Link Vehicle Density (one-way vehicles/hour)	23rd, 24th & 25th values in DNORM array	Vehicle Density	LINK (7th)	Proportional (on-link dose only)	R: 470 S: 780 U: 2800	Distribution (See Sect. 3.4.3.5)	
Population Zone Index (rural 1, suburban 2, or urban 3)	(not in code)	Pop Zone	LINK (9th)	N/A		1,2, or 3, as appropriate	Designation determines shielding factor used; rural, suburban, and urban population density ranges are the same as in NUREG-0170.
Designates link as Freeway (=1), Other roadway (=2), or Other mode (=3)	(not in code)	RD	LINK (10th)	Small		Truck: 1 Rail: 3	NUREG-0170 model assumed 5% travel on city streets and 10% on non-interstate highways. This study used 0% for both values.

Table 3.3 Comparison of RADTRAN 1 and RADTRAN 5 Input Variables that Affect Incident-Free Dose (continued)

Variable Definition	Variable Name		RADTRAN 5 Input Location	Sensitivity of Dose to Variable	Variable Value		Comments
	RADTRAN 1	RADTRAN 5	Array Name (position)		RADTRAN 1 (NUREG-0170)	RADTRAN 5 (this study)	
Fraction of land under cultivation (rural links only)	(not in code)	Farm Frac	LINK (11th)	Small (ingestion dose only)		No effect	Used to calculate ingestion dose. Not present in NUREG-0170 model; not calculated for present study.
Number of Handlers	Fixed Value	Number of Handlers per Package	HANDLING (3rd)	Proportional (handler dose only)	2	5	NUREG-0170 model only required number of handlings to be entered (7th value in DNORM array); other variables that can now be user-defined were fixed values in NUREG-0170 model. Number of handlers has been updated based on recent empirical data.
Average package-to-handler distance (m)	Fixed Value	Handling Distance	HANDLING (4th)	Proportional (handler dose only)	1	1	Value used in RADTRAN 5 based on empirical data that confirm original NUREG-0170 value.
Handling time per package (hr/package)	Fixed Value	Handling Time	HANDLING (5th)	Proportional (handler dose only)	0.5	0.5	Value used in RADTRAN 5 based on empirical data that confirm original NUREG-0170 value.
Used to calculate total exposed population for multi-year shipment campaigns	(not in code)	CAMPAIGN	MODSTD	None		20 yrs	Not present in NUREG-0170 model.
Distance-dependent rail worker exposure factor	(not in code)	DDRWEF	MODSTD	Proportional (crew/worker dose only)		0.0018 hr/km	Not present in NUREG-0170 model; used to calculate rail worker dose for crew change stops outside of classification yards.
Array of 3 distances for off-link dose calculation	(not in code)	DISTOFF	MODSTD	Inversely Proportional	(Truck: 27, 30, & 800 m)	Truck: 27, 30, & 800 m	Values were fixed in NUREG-0170 model.
Minimum distance to on-link vehicles (m)	Fixed Values	DISTON	MODSTD	Inversely Proportional	Truck: 3 m, Rail: 3 m	Truck: 3 m, Passing car: 4 m, Rail: 3 m	NUREG-0170 model did not treat passing cars.
Number of railcar inspections per trip	(not in code)	FMINCL	MODSTD	Proportional (crew dose only)		2	Used to calculate rail worker dose at classification yards. Not present in NUREG-0170 model.

Table 3.3 Comparison of RADTRAN 1 and RADTRAN 5 Input Variables that Affect Incident-Free Dose (continued)

Variable Definition	Variable Name: RADTRAN 1	Variable Name: RADTRAN 5	RADTRAN 5 Input Location: Array Name (position)	Sensitivity of Dose to Variable	Variable Value: RADTRAN 1 (NUREG-0170)	Variable Value: RADTRAN 5 (this study)	Comments
Ratio of pedestrian density to residential density	(not in code)	RPD	MODSTD	Proportional		6	Not present in NUREG-0170 model. Used to calculate dose to unshielded persons in cities.
Rural shielding factor	(not in code)	RR	MODSTD	Small	(1.0)	1.0	Recommended value reflects large fraction of time spent outdoors on farms.
Suburban shielding factor	(not in code)	RS	MODSTD	Small	(1.0)	0.87	Recommended value for wood frame construction. NUREG-0170 model assumed no shielding.
Urban shielding factor	(not in code)	RU	MODSTD	Small	(1.0)	0.018	Recommended value for masonry construction. NUREG-0170 model assumed no shielding.
Threshold dimension for handling by forklift or crane (m)	(not in code)	SMALLPKG	MODSTD	Small	(0.5 and 1.0)	0.5	RADTRAN 5 model has only one threshold – variables for large packages are defined by user.
Latent cancer fatality (LCF) conversion factors (LCF/rem) for general public and workers	ORGLCF	LCFCON	MODSTD	Proportional	2.22E-05 lung, 1.34E-5 thyroid, 1.21E-04 whole body, 6.9E-6 bone, 3.4E-6 LLI	5E-04 general public; 4E-04 workers (dose equivalent to whole-body dose)	NUREG-0170 model used organ-level factors rather than CEDE or dose-equivalent-based factors and did not distinguish public and worker populations. RADTRAN 5 model is based on BEIR V and ICRP 60.
Interdiction threshold for contaminated land (µCi/m^2)	(not in code)	INTERDICT	MODSTD	Proportional		8	NUREG-0170 model didn't include clean-up/interdiction thresholds.
Urban building fraction; fraction of land occupied by buildings (aggregate route data) or fraction of population indoors (route-specific data)	(not in code)	UBF	MODSTD	Proportional (urban dose only)		Aggregate analyses, 0.52 Route-specific analyses, 0.9	NUREG-0170 model did not account for fraction of urban area not occupied by buildings (aggregate analyses) or fraction of population in buildings (route-specific analyses).
Fraction urban land occupied by sidewalks (aggregate route data) or fraction of population outdoors (route-specific data)	(not in code)	USWF	MODSTD	Proportional (urban dose only)		0.1	NUREG-0170 model did not account for fraction of urban area occupied by pedestrians on sidewalks (aggregate analyses) or fraction of persons out of doors (route-specific analyses)

Table 3.4 Comparison of RADTRAN 1 and RADTRAN 5 Input Variables that Affect Accident Risk

Variable Definition	Variable Name		RADTRAN 5 Input Location	Sensitivity of Dose to Variable	Variable Value		Comments
	RADTRAN 1	RADTRAN 5	Array Name (position)		RADTRAN 1 (NUREG-0170)	RADTRAN 5 (this study)	
Accident Rate (accidents/vehicle-km)	APM	Accidents per vehicle-km	LINK (8th)	Proportional	Truck: 1.06E-6 Rail: 9.3E-7	Distributions (See Sect. 3.4.2)	In RADTRAN 1, for each Accident Category, APM and γ were entered as a product.
Fraction of all accidents that are of severity j	γ	Severity	SEVERITY	Proportional	8 truck and 8 rail Accident Categories (See Table 1.5)	19 truck and 21 rail Accident Categories (See Table 7.31)	In RADTRAN 1, for each Accident Category, APM and γ were entered as a product.
Fraction of package contents released in accident of severity j	RF	RFRAC	RELEASE	Proportional	8 truck and 8 rail Accident Categories (See Table 1.5)	19 truck and 21 rail Accident Categories (See Table 7.31)	NUREG-0170 values give fraction of inventory of largest release that is released for each Accident Category (see Table 1.4).
Fraction of released material that is aerosols	AER	AERSOL	RELEASE	Proportional	(1.0)	1.0	Not explicitly treated by NUREG-0170 model.
Fraction of aerosols that are respirable	RESP	RESP	RELEASE	Proportional	(1.0)	1.0	Not explicitly treated by NUREG-0170 model.
Frequencies of occurrence for Pasquill stability categories A through F (array of six values)	(not in code)	Pasquill	PARM	Proportional		Distribution (See Sect. 3.4.3.3)	RADTRAN 1 treats only a single set of weather conditions. RADTRAN 5 treats 6 sets of weather conditions.
Breathing rate (m^3/sec)	(not in code)	BRATE	MODSTD	Small	(3.3E-04)	3.3E-04	Treated as part of RADTRAN 1 inhalation dose model.
Evacuation time (days)	(not in code)	EVACUATION	MODSTD	Proportional		Distribution (See Sect. 3.4.3.2)	Because NUREG-0170 model did not treat groundshine, evacuation was not modeled.
Clean-up level ($\mu Ci/m^2$)	(not in code)	CULVL	MODSTD	Proportional		0.2	Because NUREG-0170 model did not treat groundshine, decontamination was not modeled.
Threshold for interdiction of contaminated land ($\mu Ci/m^2$)	(not in code)	INTERDICT	MODSTD	Proportional		8	Because NUREG-0170 model did not treat groundshine, interdiction was not modeled.

Table 3.4 Comparison of RADTRAN 1 and RADTRAN 5 Input Variables that Affect Accident Risk (continued)

Variable Definition	Variable Name		RADTRAN 5 Input Location	Sensitivity of Dose to Variable	Variable Value		Comments
	RADTRAN 1	RADTRAN 5	Array Name (position)		RADTRAN 1 (NUREG-0170)	RADTRAN 5 (this study)	
Latent cancer fatality (LCF) conversion factors (LCF/rem) for general public and workers	LCF	LCFCON	MODSTD	Proportional	2.22E-05 lung; 1.21E-04 whole body	5E-04 general public; 4E-04 workers (dose equivalent to whole-body dose)	NUREG-0170 model used organ-level factors rather than CEDE or dose-equivalent-based factors and did not distinguish public and worker populations. RADTRAN 5 model is based on BEIR V and ICRP 60.
Genetic effects (GE) conversion factor (GE/rem)	(not in code)	GECON	MODSTD	Proportional		1.00E-04	No genetic effects were computed in NUREG-0170 model.
Neutron emission factor for LOS accidents.	(not in code)	Neutron Emission	MODSTD	Small	(0.0)	0.0	NUREG-0170 model did not treat neutron emission. This model was not used by this study. LOS exposures were calculated from surface dose rate of an unshielded assembly.
Specifies radii for annular areas of exposure in LOS accidents	RADIST	RADIST	MODSTD	Inversely Proportional	10, 20, 30, 40, 50, 100, 200, 300, 500, and 1000 ft	3.05, 6.1, 9.1, 12.2, 15.2, 30.5, 61, 91.4, 152, 305 m	Change in units only.
1-year dose to thyroid (rem); radio-iodines only	(not in code)	RPCTHYROID	MODSTD	Small		isotope values	Used to estimate early effects.
Time needed to survey contaminated land (days)	(not in code)	SURVEY	MODSTD	Small		10	Post-accident survey and clean-up activities were not treated in NUREG-0170 model.
Time to evacuation following LOS accident (days)		TIMENDE	MODSTD	Small	1.0	R: 0.67 S: 0.67 U: 0.42	In NUREG-0170 model, this variable was defined as exposure time.
Urban building fraction; fraction of land occupied by buildings (aggregate route data) or fraction of population indoors (route-specific data)	(not in code)	UBF	MODSTD	Proportional (urban dose only)		0.52 for aggregate analyses; 0.9 for route-specific analyses;	NUREG-0170 model did not account for fraction of urban area not occupied by buildings (aggregate) or fraction of population in buildings (route-specific).
Urban sidewalk fraction; fraction land occupied by sidewalks (pedestrians) (aggregate route data) or fraction of population out of doors (route-specific data)	(not in code)	USWF	MODSTD	Proportional (urban dose only)		0.1 for all analyses	NUREG-0170 model did not account for fraction of urban area occupied by pedestrians on sidewalks (aggregate) or fraction of persons out of doors (route-specific).

the RADTRAN 5 variable value column indicates that values for this variable were selected from a real-world distribution of the values of this variable. A "fixed value" is one that was held constant throughout this study, either because it was a Less Important Variable or for the other reasons outlined previously in connection with Important Variables. If a variable that is not explicitly modeled has an implicit value or a value that is not accessible through input (i.e., a hard-wired variable), then that value is enclosed in parentheses in the RADTRAN 1 or RADTRAN 5 variable value column. In the variable value columns, R, S, and U respectively mean Rural, Suburban, and Urban. Finally, in the "Sensitivity" column, "Proportional" and "Small" have the meanings given above in the discussion of Important and Less Important Variables.

The rationale for the selection of RADTRAN incident-free and accident input variables for which distributions are constructed and the data used to construct each distribution are each presented in detail in Sections 3.3 and 3.4.

3.3 Variables Selected for Sampling

Less Important Variables are identified in Tables 3.3 and 3.4 by the word "Small" in column five, the column that specifies the sensitivity of radiation dose estimates to changes in the value of the indicated variable. Because these variables have little impact on calculated radiation doses, a central estimate value (the value listed in column seven of these tables) was selected for each of these variables and that value was used in all of the RADTRAN 5 calculations performed for this study.

More Important Variables are identified in Tables 3.3 and 3.4 by the word "Proportional" in column five. Although radiation doses are strongly affected by changes in the value of any More Important Variable, not all More Important Variables have values that take on a wide range of values in the real world. Thus, More Important Variables can be subdivided into two groups, those that have values that are constant or that vary only slightly, and those that take on a wide range of values in the real world.

3.3.1 Incident-Free Variables Selected for LHS Sampling

All variables that have proportional effects on the value of the result (i.e., Important Variables) were initially candidates for probabilistic treatment. Variables were selected for probabilistic treatment (selection of variable value by LHS sampling of the variable's distribution) principally by examination of the importance analysis performed in RADTRAN output, which shows the magnitude of the effect that a specified value change (1 percent) has on the result. As described in detail below, fixed values were assigned to those with a proportional effect but which experience little actual variation or are problem-specific. For example, incident-free dose calculations are highly sensitive to the Package Dimension variable (PKGOE in RADTRAN 1), but the characteristic dimension used in the analyses in this study is invariant for a given cask. Thus, fixed values were assigned to that variable, 5.2 m for the truck cask and 4.8 m for the rail cask (see Section 4). In contrast, an equally important variable (Package Dose Rate at 1 m) was selected for probabilistic treatment (construction of a distribution of parameter values and selection of values by sampling from the distribution), because the variety of fuel ages and burnups that characterize spent fuel causes the external dose rate of spent fuel casks to vary over a substantial range.

The incident-free variables for which distributions of parameter values were constructed are:

- Package Dose Rate at 1 m (mrem/hour)
- Link Length (km)
- Link Population Density (person/km^2)
- Persons per Vehicle (truck only)
- Link Vehicle Density (one-way vehicles/hour)
- Stop Time (truck only)

The package dose rate variable has been discussed already. Link length is treated by constructing distributions because dose to the general public residing near the road or railroad (off-link dose) is directly proportional to distance traveled and because the distances to possible destinations investigated in this study vary considerably. Link population density also directly influences risk to the general public and varies from link to link. The persons per vehicle variable directly influences dose to general public in vehicles that sharing the road with the spent fuel truck, and sufficient high-quality data regarding vehicle occupancy are now available from the Department of Transportation (DOT) to permit construction of a vehicle-occupancy distribution. Link vehicle density has a similar influence on on-link dose, and distribution data are available. The distributions used to characterize these variables are described below in Sections 3.4.1 and 3.4.3.

3.3.2 Incident-Free Variables Not Selected for LHS Sampling

The remaining variables, some of which can affect consequences or risks proportionally, include those

- that exhibit little or no actual variation,
- that cause only small changes in consequences or risks,
- for which there are not adequate data to determine the variable's distribution,
- that are problem-specific and thus have different values for specific casks (e.g., the characteristic dimension of the cask), and shipping campaigns (e.g., the number of shipments in the campaign), and
- that have no effect on truck or rail transport consequences or risks (e.g., variables used only for other modes, such as number of flight attendants).

Variables with small effects on risk and variables that vary over small ranges will be considered together.

3.3.2.1 Variables with Little or No Variation or with Small Impacts

The following variables fall into this category:

- Number of Crew Persons
- Average Distance of Crew from Package Surface (m)
- Crew Modification Factor
- Number of Railcar Inspections per Trip (FMINCL)
- Distance-Dependent Rail Worker Exposure Factor (DDRWEF)
- Number of Handlers
- Handling time per Package
- Package-to-Handler Distance (m)
- Threshold Dimension for Handling by forklift or crane (SMALLPKG) (m)
- Genetic Effects Conversion Factor (GECON)
- Latent Cancer Fatality Conversion Factor (LCFCON)

Each of these variables is now discussed even though several of them (all of the handling variables, GECON, LCFCON) are not used in any of the risk calculations performed for this study or are used only in sensitivity calculations.

The number of crew persons varies little because it is determined by trucking and rail industry practices. The value of 2 for truck transportation is by far the most common [3-10]. There is little variation in the value of this parameter, and the selected value is representative. No in-transit crew dose is calculated for rail mode because of the large separation distances and large amount of shielding between the crew and the package(s).

The average distance of crew from package surface is a new variable in RADTRAN 5. Previously, the distance from the crew compartment to the geometric center of the package was used and the same point-source model used to calculate off-link and on-link dose was used to calculate crew dose. However, for cylindrical packages such as spent-fuel casks, where the crew view of the package is from the end rather than the side, a modification of the basic point-source model yields less conservative results. For a given cask design, there is still some variability in this value because of variation in trailer length, but it is not large. The distance used is the old value less half the cask length, which relocates the crew-view point source from the geometric center of the package to the center of the side closest to the crew.

The crew modification factor is part of a new model in RADTRAN 5 intended to account for crew shielding (e.g., shielded truck cabs) and is not present in RADTRAN 1. It is a fraction that, when multiplied by the package dose rate, reflects the reduced dose rate to the crew from the presence of shielding, if any. The crew dose is limited by the maximum permissible dose rate in the crew area (2 mrem/hour). The contribution of crew dose to the total result consequently cannot exceed a maximum value, which is determined for a given dose rate by the total time in transit. Furthermore, the value of this variable has a relatively small effect on overall population dose. It should be noted, however, that the effect of dose rate changes within the subgroup itself is not necessarily small. The affected subgroup (in this case, truck or rail crew) is noted in parentheses under the column titled Sensitivity of Dose to Variable in Table 3.2.

The value of 2 assigned to FMINCL is determined by rail-carrier business practices, which require one inspection at the beginning of a trip and one at the end. The possibility of other inspections en route cannot be ruled out, but the experience base is insufficient to permit statistical treatment of this variable. Thus, the value is set to 2, the total number of inspections that are known to always occur (i.e., 1 at the beginning and 1 at end of each trip).

The DDRWEF applies to rail mode only. It is used to calculate the component of rail-worker dose that depends on distance traveled (e.g., engine changes and shift changes) rather than on time spent in a classification yard. The value of 0.0018 hour/km was determined from industry-supplied data [3-11] and is relatively invariant because of the uniformity of industry practices, union agreements, etc. Furthermore, it is a small component of total rail worker dose because the majority of the worker dose is incurred in classification yards.

The number of handlers was originally fixed at 2 in RADTRAN 1. The number is user-definable in RADTRAN 5, and the recommended value for spent-fuel handling is now 5. This recommendation is based on data from observations of 12 spent-fuel off loadings at the Port of Newport News, Virginia [3-12]. The value includes workers who guide the crane to the proper orientation for casks enclosed in ISO containers both to pick up the cask and to lower it into position on the vehicle. It also includes a spotter and workers who lock and check the tiedowns after the cask is in place. There may be more than 5 individuals involved but no more than 5 in proximity to the cask at any given time. The standardization of handling equipment means there is little variation in this value in normal operations.

Handling time per package was also a fixed value in RADTRAN 1 and was set to 1/2 hour (30 minutes). Empirical data on spent-fuel off-loadings has since confirmed that this is a somewhat conservative estimate [3-12]. As is the case for the other handling-related variables, standardization of handling equipment means there is little variation in this value in normal operations. For spent fuel casks, which are lifted with cranes, the time during which workers are in proximity to a cask is 30 minutes or less. This includes the time required to guide a crane into position; attach the crane to cask trunnions or to an enclosing ISO container; lift the cask; move it over to the transport vehicle (e.g., truck or rail car); lower it into place; fasten the tiedowns; and detach the crane once the tiedowns have been fastened. The time required for the reverse process is the same. It includes additional safety steps (e.g., checking that the tiedowns are properly secured) and also includes the time between cask movements for multiple cask handlings. Time is required, for example, for a truck to drive out of the loading zone and be replaced by a second truck ready to receive a second cask. Time is also required to reposition the crane over the next railcar, ship hold, etc. from which the next cask is to be lifted. If only one cask is being handled, then the latter actions are not necessary, which reduces the total elapsed time and makes the 30-minute value somewhat conservative.

Package-to-handler distance was fixed at 1 m in RADTRAN 1. This value has since been shown to be somewhat conservative but generally correct on the basis of empirical data [3-12] and to have little variation. It is the recommended value for RADTRAN 5.

SMALLPKG has no effect on the results for spent-fuel handling. It merely defines the minimum dimension above which mechanical handling methods must be used [3-13]. That dimension is a function of the capabilities of the package-handling machinery available and is not subject to wide variation.

Values of GECON and LDFCON are based on the most recent radiological data available. The values used must conform with federal guidance [3-14]. The values change with time, however, as more and better data become available. That is clearly seen in the difference between the 1975 and 1999 values.

3.3.2.2 Variables Where Distribution Data is Not Available

Variables for which distributions have not been developed include

- Gamma and Neutron Dose-Rate Fractions
- Rural, Suburban, and Urban Shielding Factors (RR, RS, and RU, respectively)
- Shipment velocity (km/hour)
- Urban building fraction or fraction of persons indoors (UBF)
- Urban sidewalk fraction or fraction of persons out of doors (USWF)
- Array of distances for off-link dose calculation (DISTOFF)
- Minimum distances to on-link vehicles (DISTON)
- Population density at stops (persons/km^2)
- Minimum and maximum radii of annular area around stopped vehicle (m)
- Shielding factor
- Ratio of Pedestrian Density (RPD)

Gamma and neutron dose rates vary considerably with fuel age and burn-up and the mix of fuel ages and burn-ups in any given shipment. For these reasons, especially the currently unpredictable mix of assemblies in any given shipment, no distribution of gamma/neutron ratios has been developed, and the conservative point estimates of 100 percent gamma and 0 percent neutron are used instead. This approach is conservative because neutrons are more rapidly attenuated by air and other hydrogen-rich media (e.g., concrete, shrubbery) through which they might pass during the course of normal transport prior to reaching human receptors.

The rural, suburban, and urban shielding factors were not present in RADTRAN 1 (i.e., no shielding effects were accounted for in RADTRAN 1). The variables are present in RADTRAN 5, but no distribution of weighted-average shielding factor values for urban or other areas has been developed. In lieu of such distributions, point estimates based on typical or representative construction types in the population zones have been used [3-15]. The value recommended for urban shielding (RU) in RADTRAN 5 is representative of masonry construction. The suburban factor represents frame construction. Although some suburban structures are constructed of brick or other materials, frame construction and its analogs (e.g., mobile homes) are common throughout the country. In the absence of a distribution, the frame-construction assumption also is conservative. The rural factor is set somewhat conservatively to 1.0 (i.e., no shielding) to reflect the large amount of time spent outdoors by many rural residents. No actual data on time spent indoors versus out of doors has been combined with construction-type data to generate a rural shielding factor distribution. These values were developed for RADTRAN II [3-16].

All spent-fuel shipments are highly regulated. Truck shipments have armed escorts for much if not all of their travel time. Although escorts are only required in urban areas, past experience indicates that escorts will accompany spent-fuel shipments for greater distances (e.g., in Virgina, shipments are escorted over the entire route within the state). While speeds in excess of 88 kph (55 mph) are common for ordinary commercial trucking, it is anticipated that spent-fuel shipments would not significantly exceed 55 mph. Current experience with Waste Isolation Pilot Plant (WIPP) shipments confirms this assumption [3-17]. Rail shipments travel at speeds controlled by the rail companies, and speeds for trains carrying hazardous materials are generally lower than those for general freight, although trains generally traverse urban areas at reduced speeds.

In the absence of adequate data from which to construct truck or train speed distributions, the typical interstate truck speed and typical train speeds for hazardous material shipments were used as point estimates. Thus, shipment velocity is set to 88 kph (55 mph) in all population zones for interstate truck transportation. For rail transportation, different values were used for rural, suburban, and urban route segments: 64.37 kph (40 mph) on rural segments; 40.3 kph (25 mph) on suburban segments; and 24.1 kph (16 mph) on urban segments. Because these speeds are believed to be somewhat conservative (lower than may actually occur), they should lead to a small overestimation of incident-free dose. Because these speeds are not used to estimate cask impact speeds during collision accidents, they have no effect on accident risks.

UBF and USWF were not present in RADTRAN 1. They were added in RADTRAN II. At that time, aggregated population-density data was the only type of population information available. The population density assigned to urban links, therefore, was treated as being uniform across the entire bandwidth (area within 800 m on either side of the road or railroad). This would have led to an overestimate of the off-link urban population if used without modification. The UBF and USWF correction factors restricted population to areas occupied by buildings and sidewalks; the values came from the Urban Study [3-18]. In current analyses, however, population densities are derived from GIS-based systems with census-block population data. That is, they represent *actual counts* that should not be reduced by any correction factors. Thus, the UBF and USWF values are now used to simply designate what fraction of the population is indoors and what fraction is out of doors. The sum of the two fractions must now be unity. The data indicating what fraction of the urban population is out of doors at any given time are from the Urban Study, which examined only New York City. The 0.1 estimate (10 percent), which applies only to a weekday during working hours in Manhattan, has been used as a conservative point estimate; the 0.9 indoors value (90 percent) was obtained by subtraction from 1.0. The Manhattan value is conservative because of the number of workers who are out of doors for significant portions of the workday (e.g., garment-district carriers and messengers).

DISTOFF consists of an array of three distances, the first two of which define a pedestrian zone adjacent to the road or railroad and the last of which establishes the maximum depth or bandwidth for off-link dose calculation. These variables were present in RADTRAN 1 and have not changed since 1975. There undoubtedly is variation in the minimum distance to the road at which people may reside; it may frequently be greater than 30 m and occasionally may be less, but no distribution for this variable is available in the literature. The maximum distance was set at 800 m (0.5 mi) in the 1975 model to conform with the previously published Reactor Safety Study [3-8] although dose rates drop below measurable values at much shorter distances from the road or railroad. All analyses since then have used the same value, and, even though RADTRAN 5 allows the value to be altered, 800 m is used here to provide comparability with earlier studies. The pedestrian zone width was set at 3 m in RADTRAN 1 on the basis of civil-engineering standards for walkway widths, and in the absence of any data to support use of a distribution, the 3 m width also is used here to provide comparability.

DISTON is used in the calculation of on-link dose and is the minimum distance from the package to traffic in nearby lanes. The user enters up to four values for interstate highways, secondary roads, city streets, railroads, and passing vehicles, respectively. The interstate value is based on a 1986 model of a minimal four-lane configuration with an average lane width of 5 m. The secondary and city-street values, which are smaller (3 m), are not used in this study. The railroad value of 3 m is based on the minimum clearance between passing trains on double-rail route segments. The value for passing vehicles (4 m) is the median value for all interstate and secondary-road lane widths. These variables are not equally uncertain. The minimum interstate lane width, for example, is determined by engineering standards that apply to all interstate highways. However, no published data are available that indicate the range of magnitudes of these variables, and the point estimates described above are used here.

Two population densities are used to calculate public dose at ordinary truck stops (rest and refueling stops). The first population density is a derived value that yields approximately nine persons fully unshielded within a 10-m radius in order to conform to the observations of Griego et al. [3-19]. The second density is used to calculate exposures to more distantly located persons. It is set equal to the suburban aggregate value used in the 1975 model since it is not possible to predict exact stop locations in advance. The Griego et al. study [3-19] examined two separate truck stops, one suburban and one rural in nature. Their data include many hours of observation of truck-stop operations. The standard deviation of their data for persons within 10 m is small. The reasons for this uniformity are that

- truck stops provide standardized services (refueling bays, restaurants, etc.),
- service area and refueling bay designs tend to be standardized, and
- truck parking parameters (average row spacing and average distance from the service area) have low variability.

Thus, the mean value of the Griego et al. data [3-19] was used in this analysis for the inner annulus of truck stops. For rail stops, public dose is also estimated using the suburban aggregate population density. This is done because most rail yards are located in regions with suburban population densities, and because a distribution for this variable can not be constructed without knowing the actual locations of rail stops, which of course can only be specified for the real routes used during a real shipping campaign.

The minimum and maximum radii in RADTRAN 1 established an annular area around a stop location in which exposed persons were located. They were arbitrarily fixed at 10 ft (≈ 3 m) and 2600 ft (≈ 800 m). Recent observations of actual truck stops have shown that the minimum is too large [3-19]. The minimum approach distance was in the 1 m range. These observations also led to the partitioning of the surrounding population into two nested annular areas. The innermost annulus has minimum and maximum radii of 1 and 10 m, and all persons within the area are unshielded; the outer annulus has minimum and maximum radii of 10 and 800 m, respectively. Proximity of the shipment to structures and other trucks provides some shielding for this outer population. For calculation of public dose at rail stops in classification yards, the minimum radius coincides with the typical classification-yard boundary (400 m) and the maximum radius remains 800 m. For rail stops outside of classification yards, the minimum radius is 30 m and the maximum radius remains 800 m. The maximum radius is set to 800 m solely to provide calculational consistency between modes and between stop-related and in-transit contributions to dose. In the absence of advance knowledge of stop locations, exact minimum values cannot be used, and no distribution of population densities around possible stops has been developed.

The shielding factor is set to 1.0 (no shielding) on the basis of the data in [3-19] for the inner annular area at truck stops (radii of 1 m and 10 m). References [3-19] and [3-10] are the basis for the selection of 0.2 as a shielding factor for the outer annular area. The shielding factor of 0.1 for rail classification stops was calculated in [3-11]. The shielding factor for rail stops outside of classification yards has been set to a conservative 1.0 because of the lack of empirical information on presence or absence of surrounding structures at intermediate rail stops. No distribution that describes the frequency distribution of shielding factors for public exposure at either truck or rail stops has been developed.

The ratio of pedestrian density allows the user to account for persons out of doors in urban areas and persons who are not residents (shoppers, drivers, etc.). It acts as a direct multiplier for the out-of-doors urban population. The value used in this study is 6 and it is taken from the Urban Study [3-18], which examined only New York City. The value is generally conservative because commercial districts remain robust, unlike many other American cities where much of the business activity has relocated to suburban shopping centers and industrial parks. The ratio of the number of retail businesses to the residential population is 6.95 for New York City, as opposed to values near 1 for most other East Coast cities (e.g., 1.01 for Boston); it also is greater than the same ratio for large West Coast cities such as Los Angeles (ratio = 5.65) [3-20]. No distribution of values for this variable has been developed.

3.3.2.3 Problem-Specific Variables

Problem-Specific Variables include:

- Characteristic Package Dimension (m)
- Number of Shipments
- Number of Packages per Shipment
- DTSTOR (Storage time per shipment; hours)
- PDSTOR (Number of persons exposed during storage)
- RSTOR (Radial distances defining annular area within which persons are located around storage location)
- Crew-view Package Dimension (m)
- Distance of crew from nearest package (m)

As noted in the introduction to this section, the characteristic package dimension is determined by the choice of package for a given analysis. The values used in this study are 5.2 m for the truck cask and 4.8 m for the rail cask (see Section 4).

The number of shipments is a variable found in all releases of RADTRAN. It clearly is problem-specific. All of the RADTRAN calculations performed for this study examined single shipments that transport one spent fuel cask, i.e., the number of shipments was set to one, and the number of shipments required to ship the entire on-site spent-fuel inventory (e.g., all of the spent fuel assemblies that will have to be shipped from the sites where they are presently stored) to a repository or intermediate storage facility is addressed in external calculations (spreadsheet). The number of shipments needed to move the spent fuel inventory from on-site storage locations to temporary or permanent storage facilities is discussed in Section 8.6.

The number of packages per shipment also is found in all releases of RADTRAN. For the analyses performed for this study, it was assumed that each shipment carried only one Type B spent fuel cask. This assumption is clearly correct for transport by truck. For transport by rail, it is generally correct when transport is not by dedicated train (shipment by dedicated train was not examined by this study).

The RADTRAN 1 variables DTSTOR, PDSTOR, and RSTOR are not present as distinct variables in RADTRAN 5 because storage is modeled as a special type of stop in RADTRAN 5. No en route storage is anticipated in the spent-fuel shipments analyzed in this study, so storage variables are set to zero for RADTRAN 1 and no special storage stop is modeled in RADTRAN 5.

The crew-view package dimension, like the basic package dimension variable, is determined by the choice of cask and has no associated uncertainty. The values used in this study are 2 m for the truck cask and 5 m for the rail cask.

3.3.2.4 Variables that Do Not Affect Truck or Rail Spent Fuel Transport

There are several variables that do not contribute to dose or risk calculation for spent-fuel transportation by truck and rail modes. They are

- Number of Flight Attendants (FNOATT)
- Fraction of Land under Cultivation
- Exclusive-Use Flag (computer code "switch")
- Population Zone
- Link Type
- CAMPAIGN

Some variables have no effect on the result in this study, regardless of what values are assigned to them. One of these is the number of flight attendants; it applies only to modes of transportation (air modes) not considered in this study. The term "No Effect" is entered for this variable in the Variable Value column in Table 3.1, and no value is entered for FNOATT in the input file. The fraction of land under cultivation variable has no effect on the result in this study because ingestion dose is not computed.

Several flags and control variables found in RADTRAN 5 also should be mentioned. The first of these is the flag for exclusive-use versus non-exclusive use. It is set to exclusive use in all cases in this study. The population zone designation (rural, suburban, or urban) determines which shielding factor is used and what column the link results are entered into in the output. The designation is problem-specific. The designator was intended to allow use of non-standard shielding factors (e.g., use of an "urban" shielding factor in non-urban links with high proportion of masonry construction. However, such highly route-specific data are not employed in this study and the designator thus depends on the definitions of rural, suburban, and urban population densities. The latter are 0 through 66 person/km^2 for rural; 67 through 1,670 persons/km^2 for suburban; and greater than 1,670 persons/km^2 for urban. These ranges were derived from the demographic model in NUREG-0170, and they have been used to develop population zone data for all releases of RADTRAN. The letters R, S, and U are used to designated rural, suburban, and urban zones in RADTRAN 5. A related variable is the Link Type designator. It is set to 1 for interstate highways, 2 for other highway types, and 3 for rail or other modes. These designations are completely problem-specific, and there is no uncertainty as to what value is entered for each link once the route has been established.

The CAMPAIGN variable has no direct effect on the result. It is used to calculate the total off-link population for multi-year campaigns by taking account of in-migration and out-migration of population. It is based [3-21] on 1990 Census Bureau demographic data.

3.3.3 Accident Variables

This section gives information on RADTRAN variables required for accident-risk analysis (Table 3.4). The format is the same as that used for incident-free variables. Variables were selected for probabilistic treatment on the basis of sensitivity analyses performed to determine the magnitude of change in the result associated with a fixed amount of change in an input value.

3.3.3.1 Accident Variables not Selected for LHS Sampling

The following accident-risk variables have been assigned point-estimate values

- Sidewalk Width in early effects calculation (m)
- Building Dose Factor
- Clean-up Level (CULVL) (microCi/m^2)
- Threshold for Interdiction of Contaminated Land (microCi/m^2)
- Time to Survey Contaminated Land (days)
- Breathing Rate (m^3/sec)
- Neutron Emission Factor for Loss of Shielding (LOS) Accidents
- One-year Dose to Thyroid (rem/rem inhaled)
- Radii of annular areas of exposure in an LOS Accident
- Time for Evacuation following an LOS Accident (hours)

Sidewalk width was a RADTRAN 1 variable and is no longer included as a variable in RADTRAN 5. It was used only in calculation of dose to persons following an LOS accident on a city street. Because travel on city streets during spent-fuel transportation historically has occurred only in the case of overseas shipment into U.S. ports, no travel on city streets is considered in this analysis, the model in which the variable is used in RADTRAN 1 is not invoked and no correlation or adjustment is necessary.

The building dose factor is used to account for filtration of particulates from the air by building heating/cooling systems. It was not included in RADTRAN 1. The recommended value of 0.05 for RADTRAN 5 is taken from [3-11]. This value is an average across a number of residential, office, and industrial building types and represents the best available estimate in the absence of a distribution.

Clean-up level (CULVL) was not a variable in RADTRAN 1. This variable is not treated probabilistically because it is defined by regulation. Although there is currently no final guidance for the value of the regulatory clean-up level, draft guidance issued by the U.S. Environmental Protection Agency, recommends a value of 0.2 microCi/m^2 [3-22]. This value is used in all of the RADTRAN calculations performed for this study. Like the clean-up level, there is currently no final regulatory guidance for the Interdiction Threshold contamination level. The value selected for use is 40 times higher than the value selected for CULVL, because the decontamination factors achieved cleaning up two cases of weapons-related contamination [3-23] suggest that decontamination of areas of moderate size by factors as large as 40 is achievable.

The actual time required to perform a contamination survey would likely be prolonged, but it is not possible to predict because of regulatory and legal complexities [3-23]. The longer deposited material remains on the ground, however, the more is (a) removed by radioactive decay and (b) spread by forces such as wind and rain. In general, the shorter the elapsed time between an accident occurrence and completion of a survey, the higher the survey results would be. Furthermore, because of the rarity of actual contamination events, there is a paucity of empirical data on which to base an estimate. For these reasons, the time to survey contaminated lands was set at a radiologically conservative but practically unrealistic 10 days. The legal and practical realities associated with post-accident response are discussed in Chanin and Murfin [3-23].

The generally accepted standard for breathing rate is used for calculation of inhalation and resuspension doses. The breathing rate of the International Council on Radiation Protection Reference Man (70-kg adult male at light work) is the recommended value; it is 3.3E-04 m^3/sec [3-24]. While not a quantity prescribed by regulation, this variable was developed by a recognized international body (International Council on Radiation Protection) and is commonly used in radiological consequence calculations. Thus, there is no need to treat this variable probabilistically.

The dose-conversion factor for one-year dose to the thyroid is used to calculate thyroid dose via the inhalation pathway. The factor is applied only to radioisotopes of iodine. Values specific to I-131, I-129, and I-125 have been developed for this variable and they are: 1.26E-06, 5.77E+06, and 9.25E+05 rem/Ci inhaled, respectively. These are radiological quantities and are not subject to probabilistic treatment. Because none of the inventories used in this study contain significant quantities of radioiodines, the value of this parameter is not important.

3.3.3.2 Accident Variables Selected for LHS Sampling

The accident variables selected for probabilistic treatment and the sections that describe the treatments are:

- Accident Rate on a Link (accidents/vehicle-km) − Sections 3.4.2.2 and 3.4.2.3
- Evacuation Time − Section 3.4.3.2
- Atmospheric Stability − Section 3.4.3.3

3.4 Development of Distribution Functions

3.4.1 Route Characteristics

3.4.1.1 Introduction

The present study, which is intended to address the risk of transporting spent nuclear fuel from all commercial power reactors to a repository, posed an unusual difficulty. While the locations of the reactors where spent fuel is presently stored are known, final locations for interim storage sites and for a permanent repository have not yet been selected and formally approved. Therefore, specific spent fuel shipment routes could not be examined and small set of hypothetical routes could be shown to be truly representative of all of the routes that might someday be used. The method chosen to address this difficulty was to develop distributions of shipment parameters and route characteristics using data for a very large number of real routes that connect reactor sites to plausible interim storage site and permanent repository location, and then to construct representative set of route parameter values by sampling these distributions using LHS sampling methods. Provided that the distributions constructed represent the full spectrum of possible routes and that sufficient sets of RADTRAN input variables (generated by sampling the distributions) are analyzed, the mean risks and the risk ranges estimated using these sets of route parameter values should accurately represent actual shipment risks.

The set of primary shipment origins is well known (commercial reactors with spent fuel in holding pools). One possible interim storage site location was identified in the northeast, north-central, northwest, southeast, south-central, and southwest portions of the continental United States. In addition, three possible permanent repository locations, one of which was Yucca Mountain, were also selected. The set of interstate truck routes or mainline rail routes that connect each reactor site to each of the possible interim storage sites and each of these interim storage sites to each of the three possible permanent repository locations were examined by performing HIGHWAY [3-25] or INTERLINE [3-26] route calculations. In the case of truck shipments, the routes were specified in compliance with HM-164 rules for "highway route controlled quantity" shipments (49 CFR 177.825) such as the spent nuclear fuel shipments considered here. For rail shipments, the routes conformed to rail carrier practice. For both types of shipments, any NRC regulations (10 CFR 73.37) that would affect route selection were considered.

After the routing calculations were completed, a data base of the lengths, and rural, suburban, and urban length fractions was constructed using the data for the 492 truck or the 492 rail routes. Sets of parameter values from each data base were ordered and aggregated to create cumulative distributions for each of these route parameters. In Figures 3.1a through 3.1d, these NEW distributions for truck routes are compared to OLD distributions constructed from similar sets of route data tabulated in the Yucca Mountain down-select report [3-27]. Figures 3.2a through 3.2d present a similar comparison of NEW and OLD rail-route parameter distributions. After visual inspection of these distributions indicated that each NEW distribution was very similar to its corresponding OLD distribution, the two data sets were combined thereby generating a larger, statistically more comprehensive data base. The final set of route parameter distributions was then constructed using the pooled data.

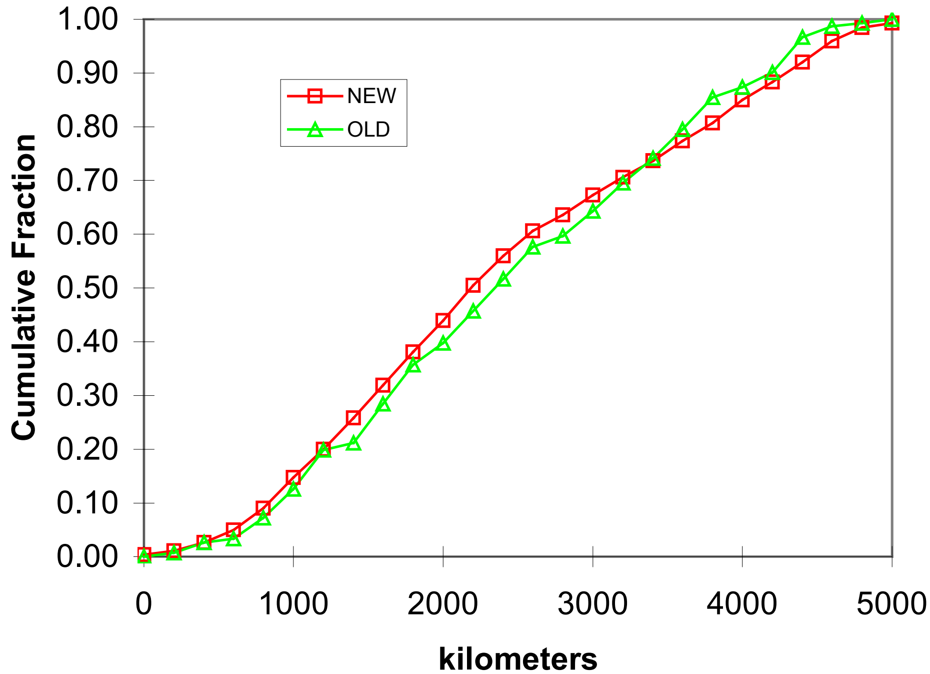

Figure 3.1a Comparison of the cumulative distributions of route *lengths* for truck.

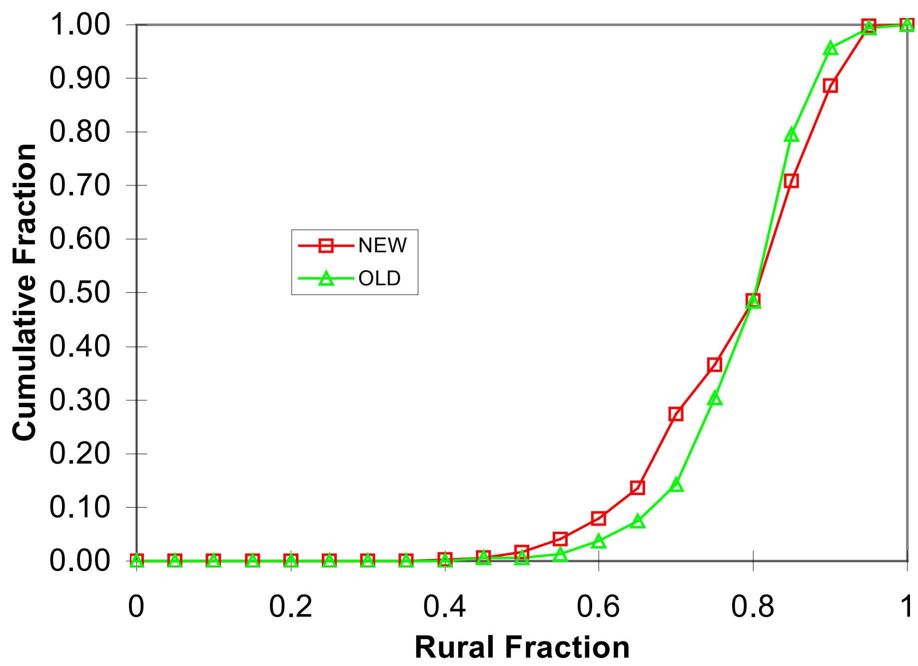

Figure 3.1b Comparison of the cumulative distributions of route *rural fractions* for truck.

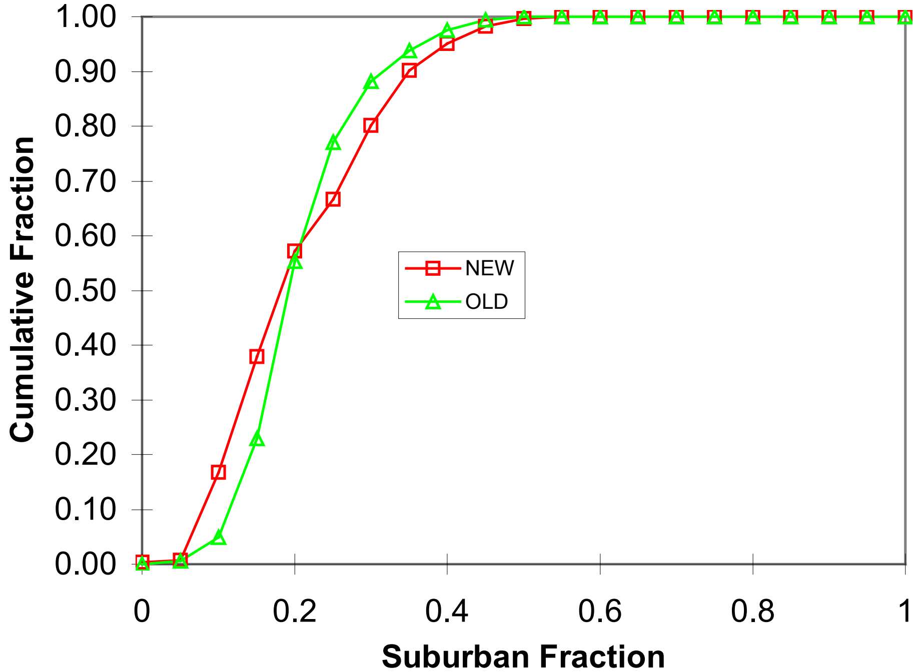

Figure 3.1c Comparison of the cumulative distributions of route *suburban fractions* for truck.

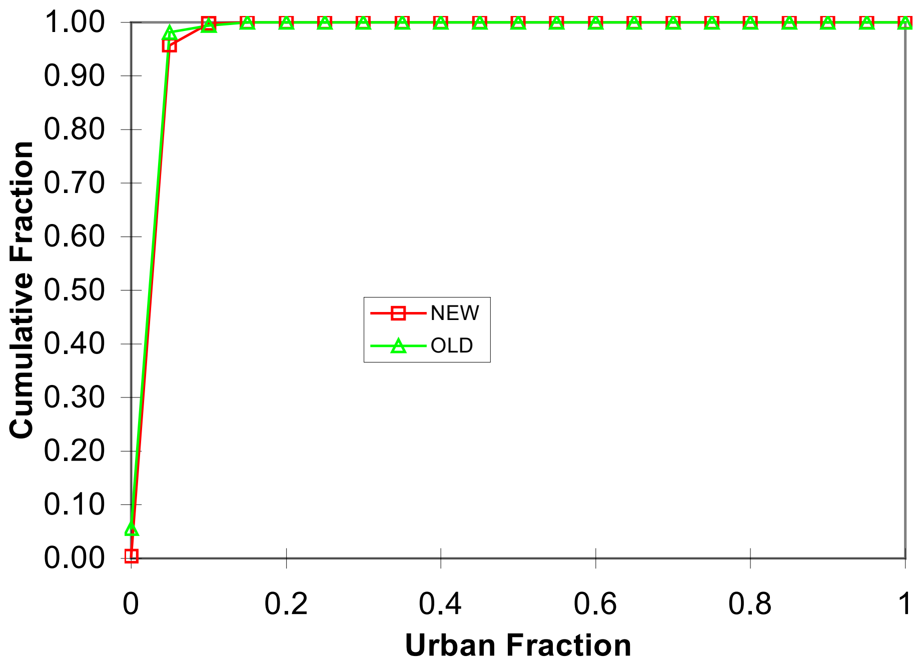

Figure 3.1d Comparison of the cumulative distributions of route *urban fractions* for truck.

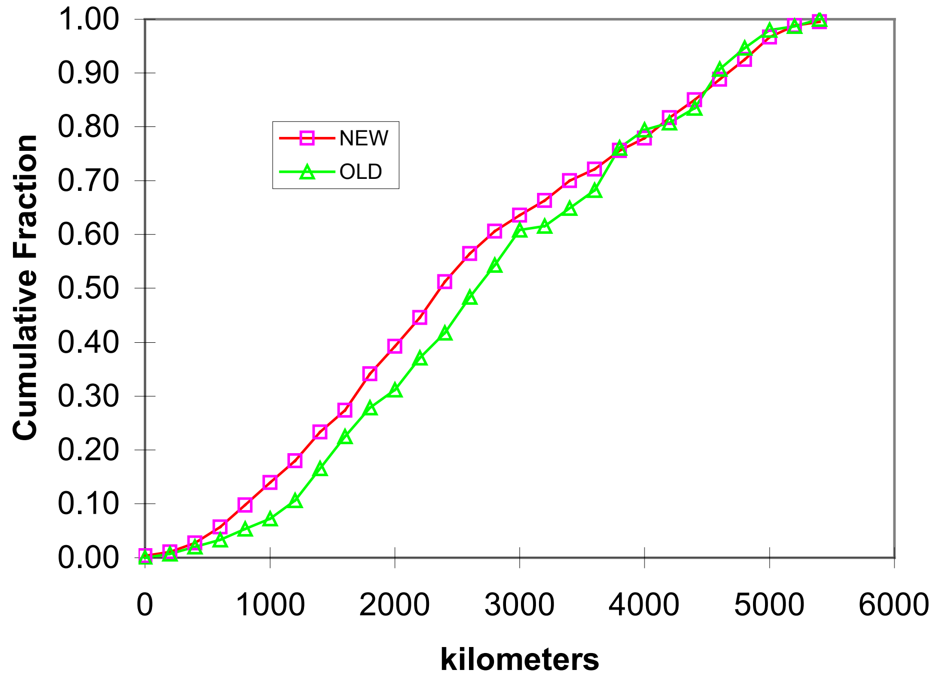

Figure 3.2a Comparison of the cumulative distributions of route *lengths* for rail.

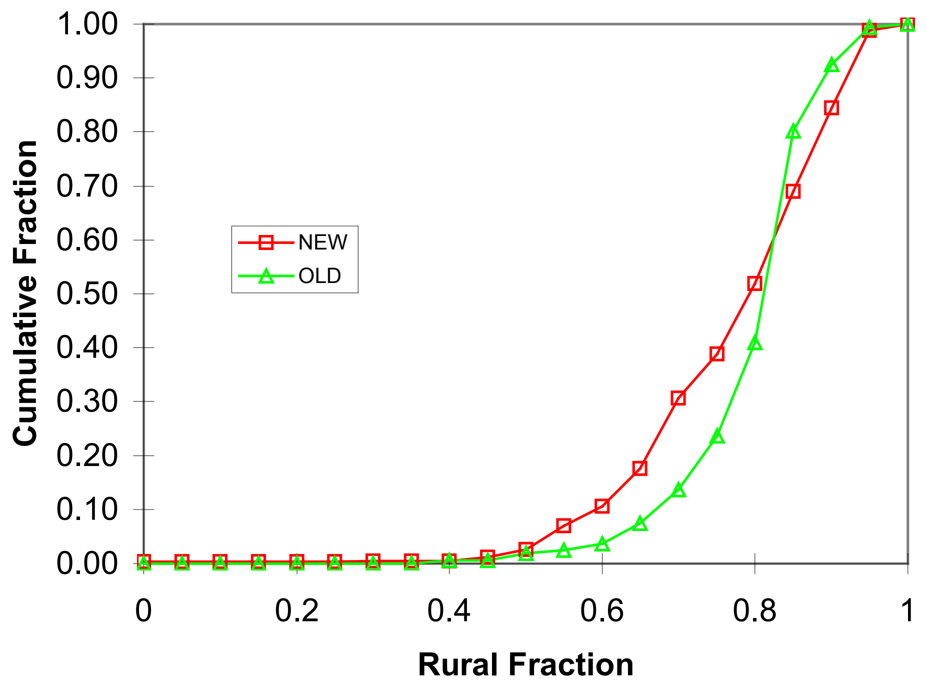

Figure 3.2b Comparison of the cumulative distributions of route *rural fractions* for rail.

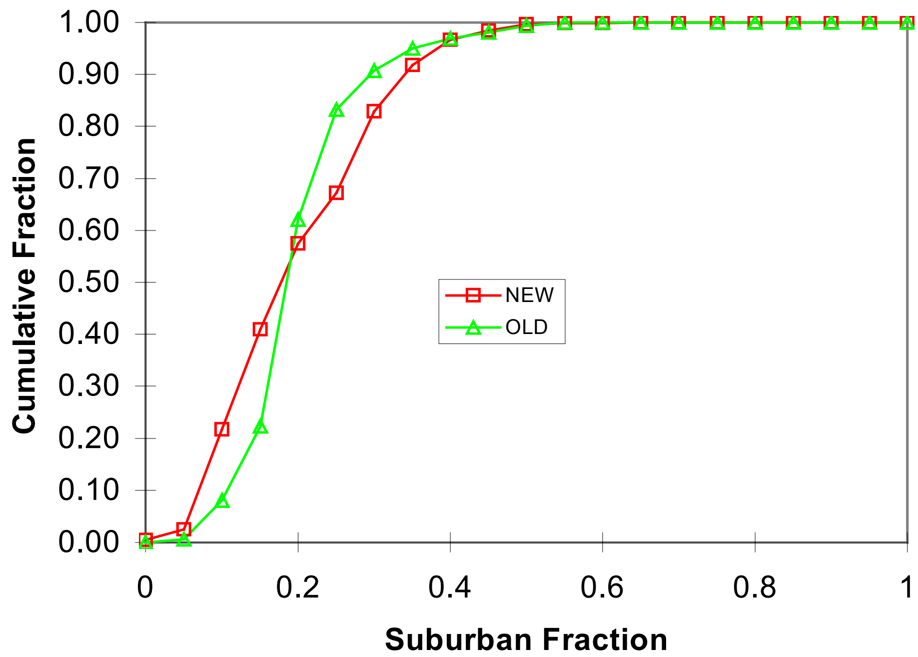

Figure 3.2c Comparison of the cumulative distributions of route *suburban fractions* for rail.

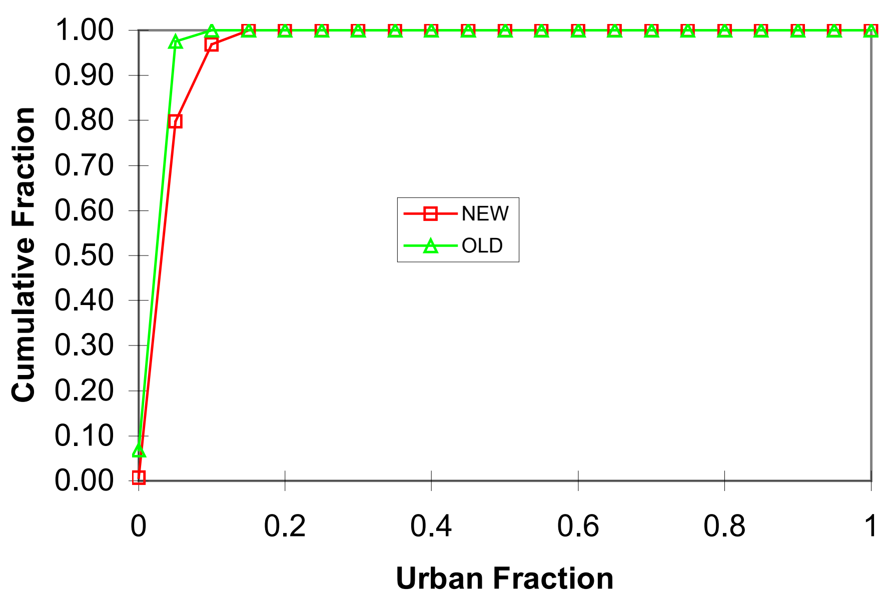

Figure 3.2d Comparison of the cumulative distributions of route *urban fractions* for rail.

3.4.1.2 Route Lengths

The length of any route is a key parameter in determining the risks associated with that route because accident probabilities on the segments of a route are the products of the accident rate (number per vehicle-km) and the length of each segment. In addition, incident-free doses are proportional to route length (e.g., total stop time and driver exposure time for truck shipments) and route-length multiplied by population-density (populations sharing and neighboring the route). Histograms of route lengths derived from the combined route data are presented in Figures 3.3a and 3.3b respectively for truck and rail routes. Integration of these histograms and normalization to a total cumulative probability of 1.0 yielded the final cumulative route-length distributions presented in Figures 3.4a and 3.4b.

3.4.1.3 Rural, Suburban, and Urban Route Fractions

The same data base described in Section 3.4.1.1 provided values for the aggregate fractions of each route that traversed areas with Rural, Suburban, or Urban population densities. Table 3.5 presents the population densities ranges that were used in NUREG-0170 and in this study to define urban, suburban, and rural route segments.

Table 3.5 Definition of Population Density Categories (persons/km^2)

Category	Minimum	Maximum	Mean
Rural	0	66	6
Suburban	67	1670	719
Urban	1670	- - -	3861

Histograms of the Rural, Suburban, and Urban fractions, constructed from the combined data, are shown in Figures 3.5a and 3.5b. The cumulative distribution functions derived from these histograms, are presented in Figures 3.6a and 3.6b.

3.4.1.4 Rural, Suburban, and Urban Population Densities

As part of the route compilation described in Section 3.4.1.2, the distance-weighted average population density values for the rural, suburban, and urban categories were also tabulated in the route characteristics data base. Values for truck routes were sorted and aggregated, then integrated and normalized to create the histograms and cumulative distributions shown in Figures 3.7a through 3.7c; similar processing of the rail route data yielded the plots in Figures 3.8a through 3.8c. Note that the Urban values in Table 3.5 were influenced by the inclusion of city-street route options while the present study is limited to interstate highways and loops that do not traverse such high population-density areas.

3.4.1.5 Application Notes

Each of the cumulative distributions presented in the following figures serves as input to the LHS sampling code. Sampled values of route length, route fractions, and segment population

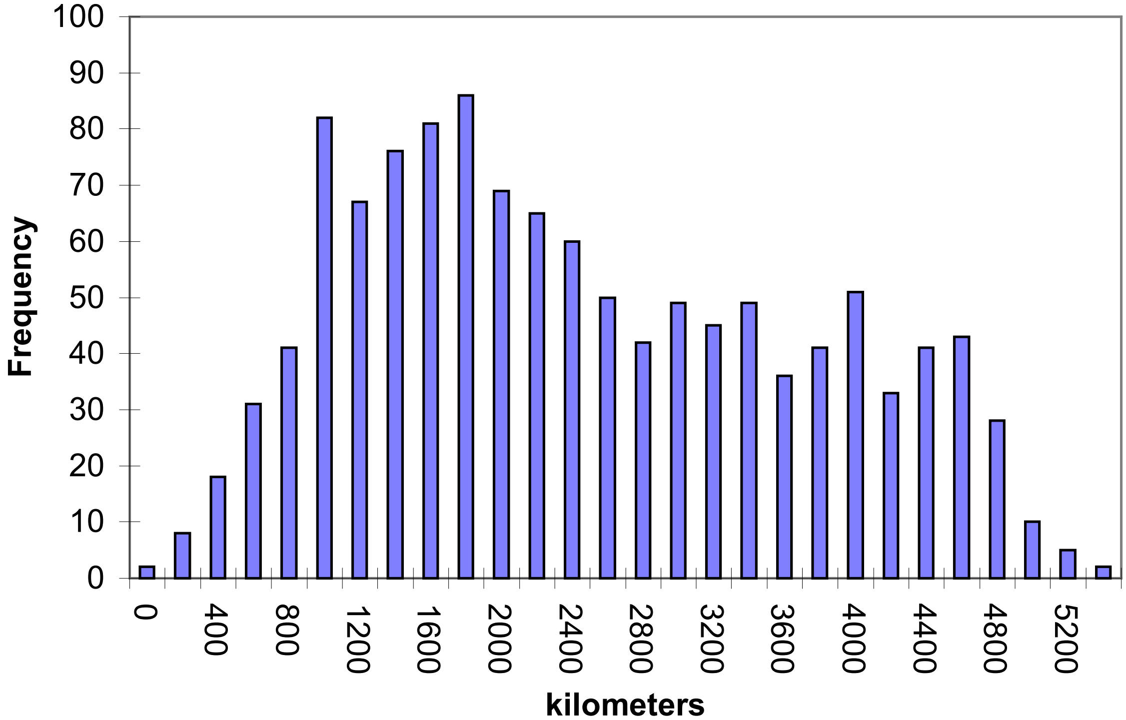

Figure 3.3a Histogram of truck route lengths.

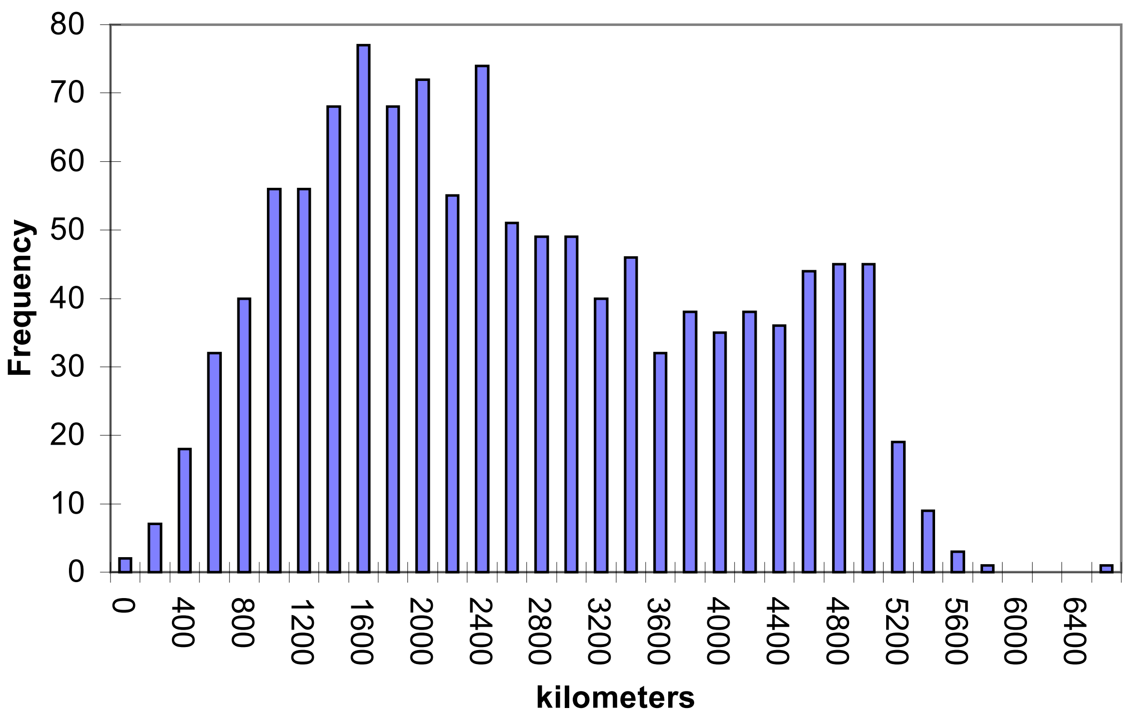

Figure 3.3b Histogram of rail route lengths.

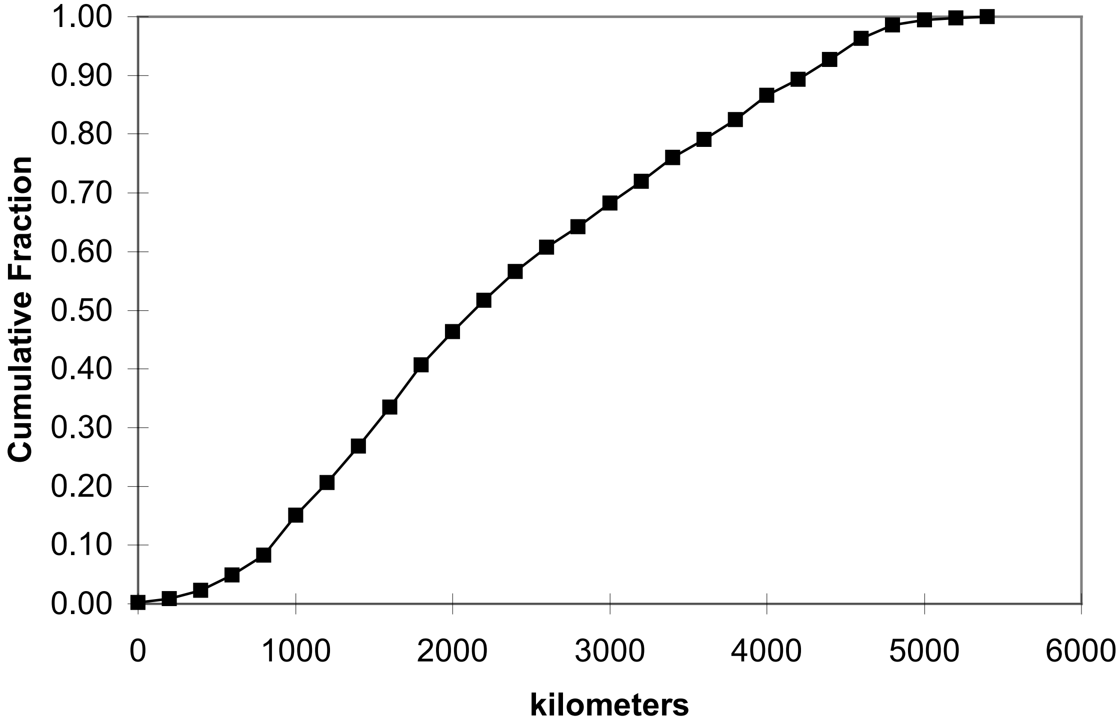

Figure 3.4a Cumulative distribution of truck route lengths.

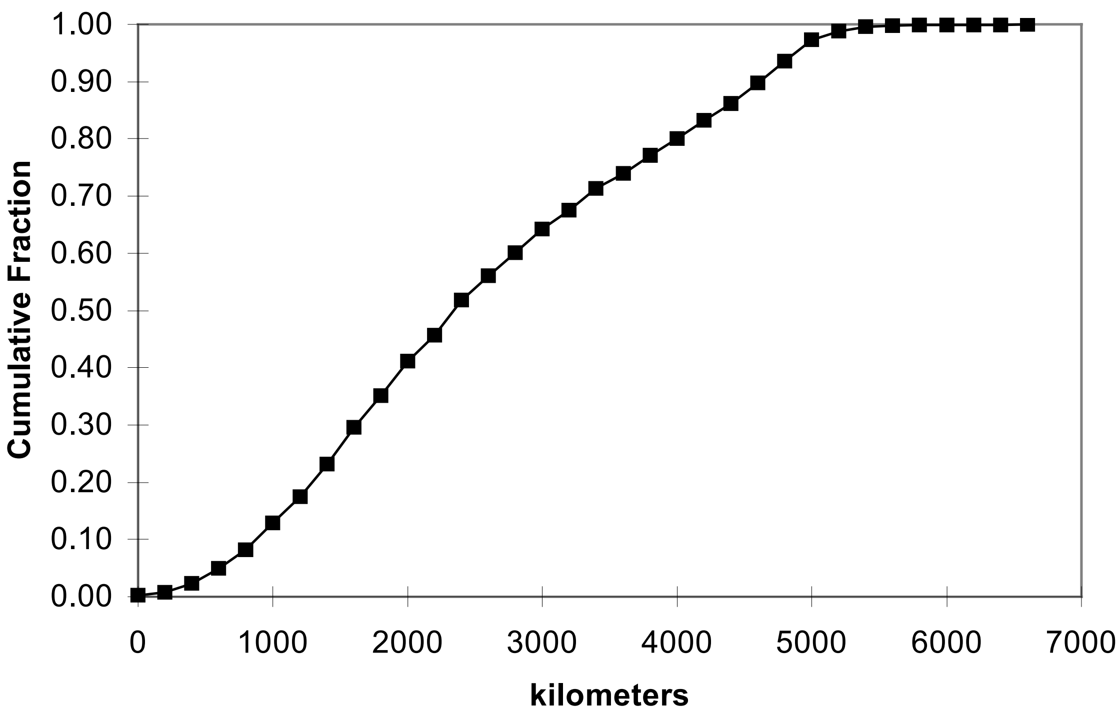

Figure 3.4b Cumulative distribution of rail route lengths.

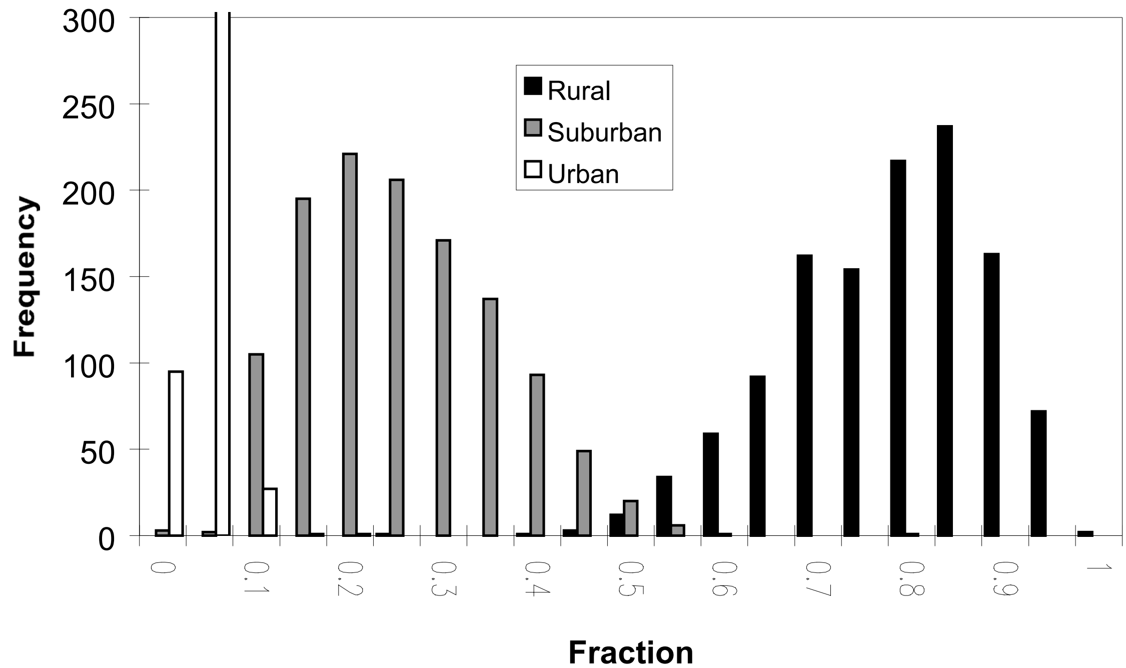

Figure 3.5a Histograms of rural, suburban, and urban length fractions for truck routes.

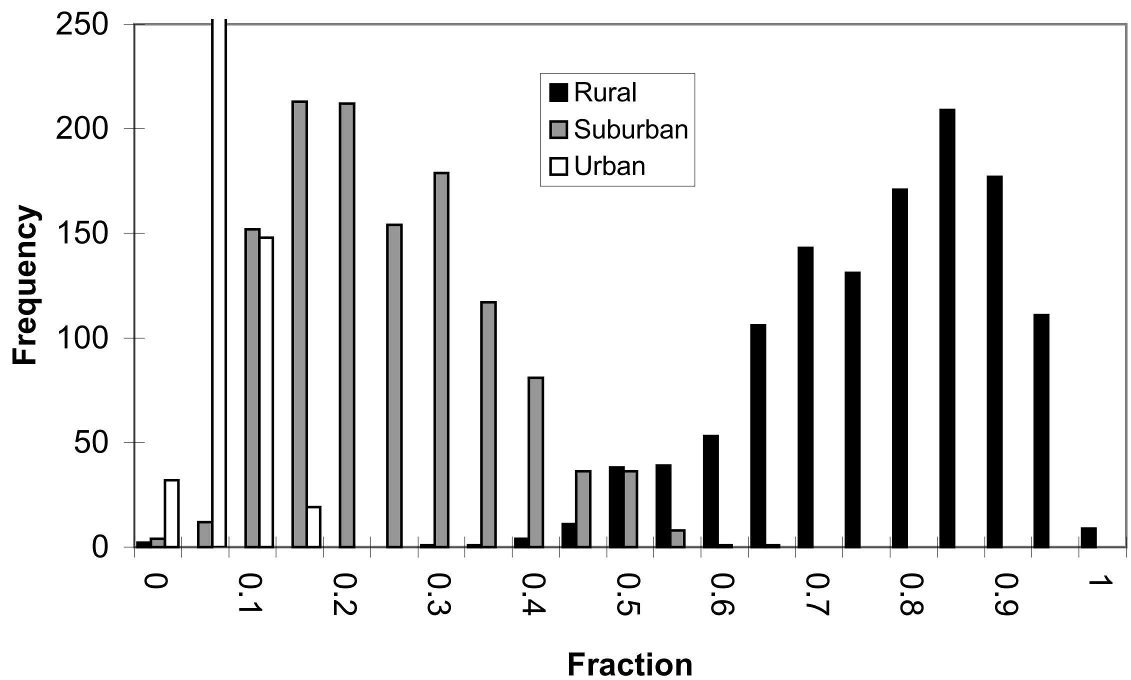

Figure 3.5b Histograms of rural, suburban, and urban length fractions for rail routes.

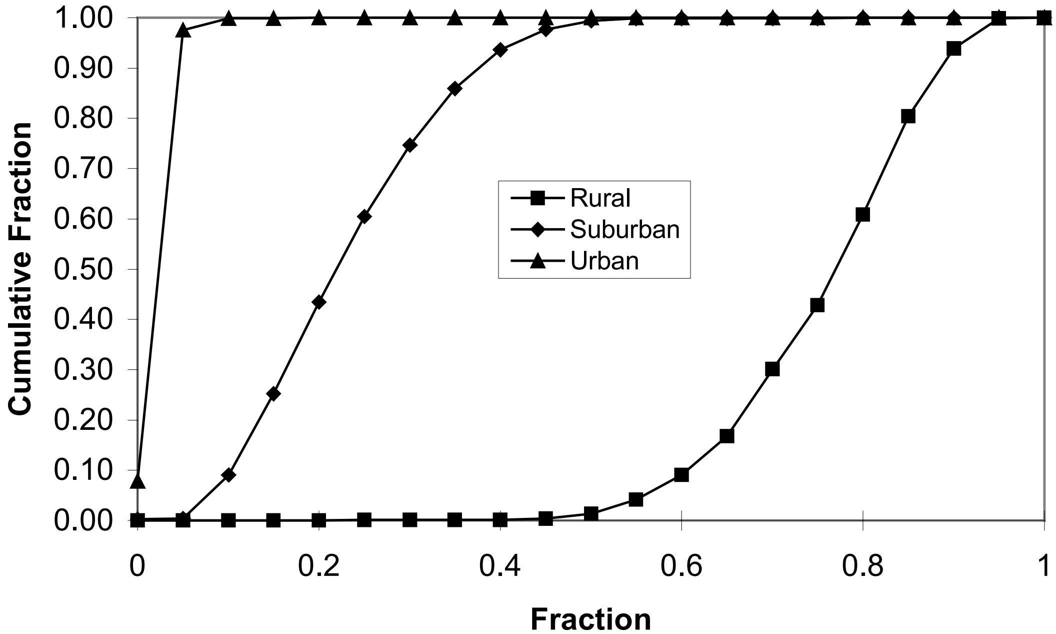

Figure 3.6a Cumulative distributions of rural, suburban, and urban length fractions for truck routes.

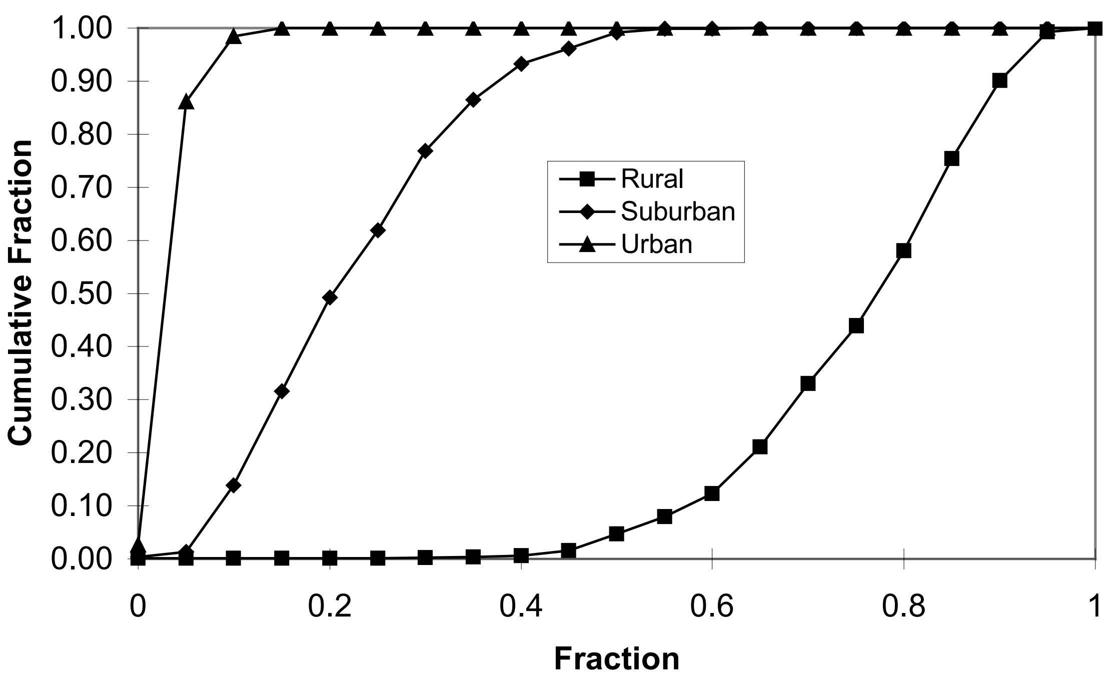

Figure 3.6b Cumulative distributions of rural, suburban, and urban length fractions for rail routes.

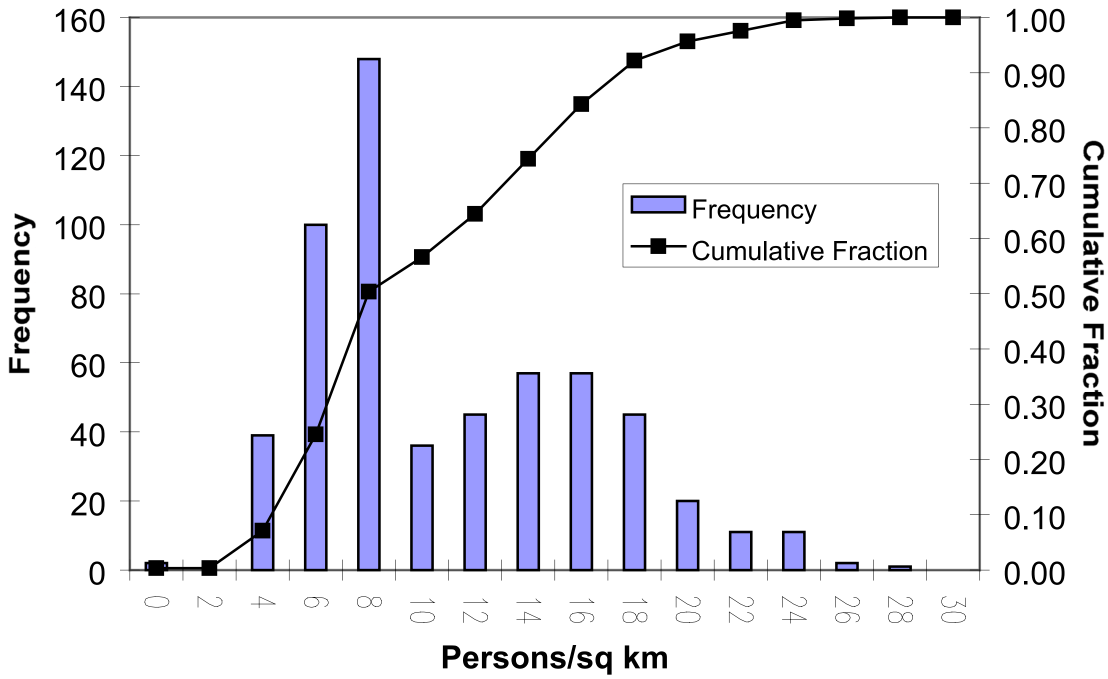

Figure 3.7a Histogram and cumulative distribution for *rural population density* for rural truck route segments.

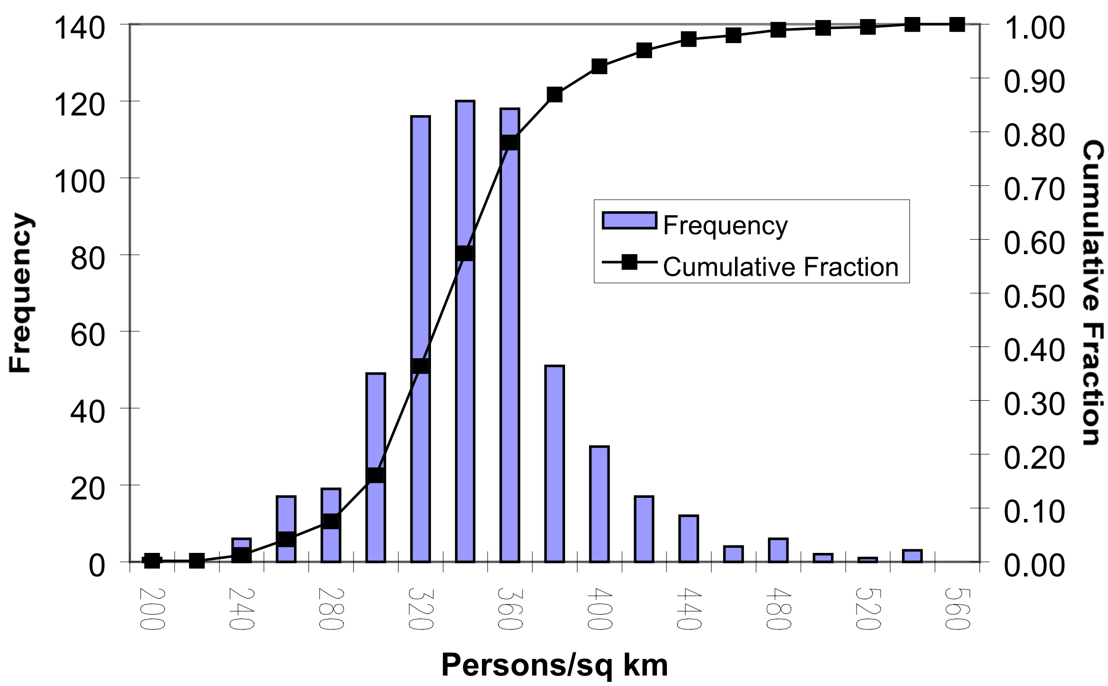

Figure 3.7b Histogram and cumulative distribution for *suburban population density* for suburban truck route segments.

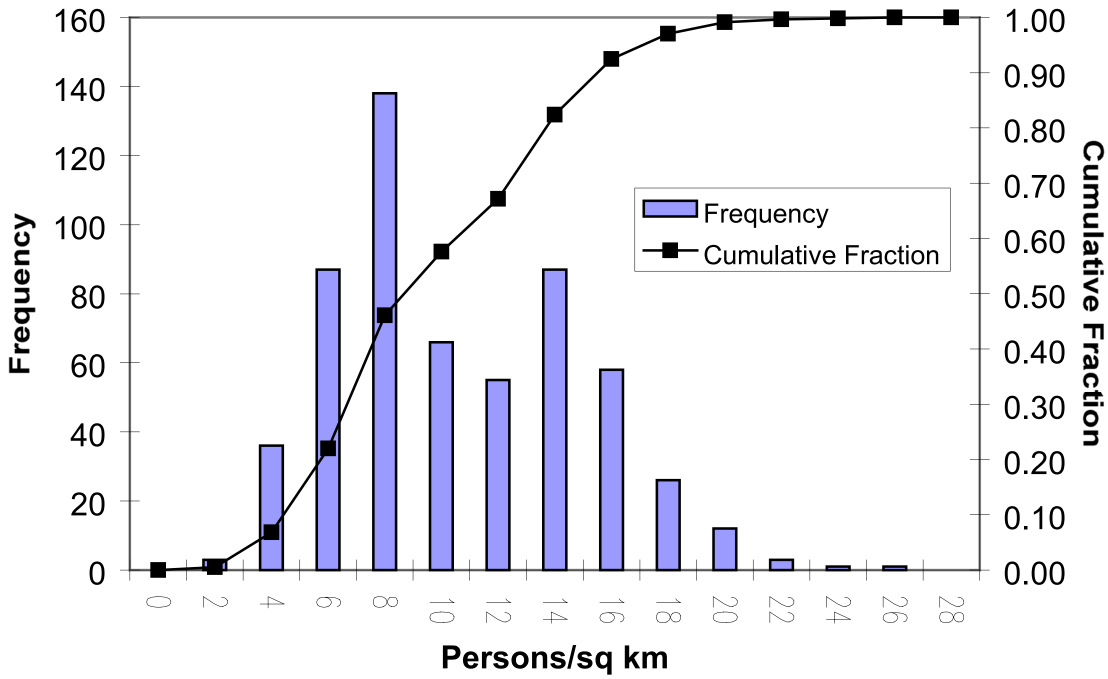

Figure 3.7c Histogram and cumulative distribution for *urban population density* for urban truck route segments.

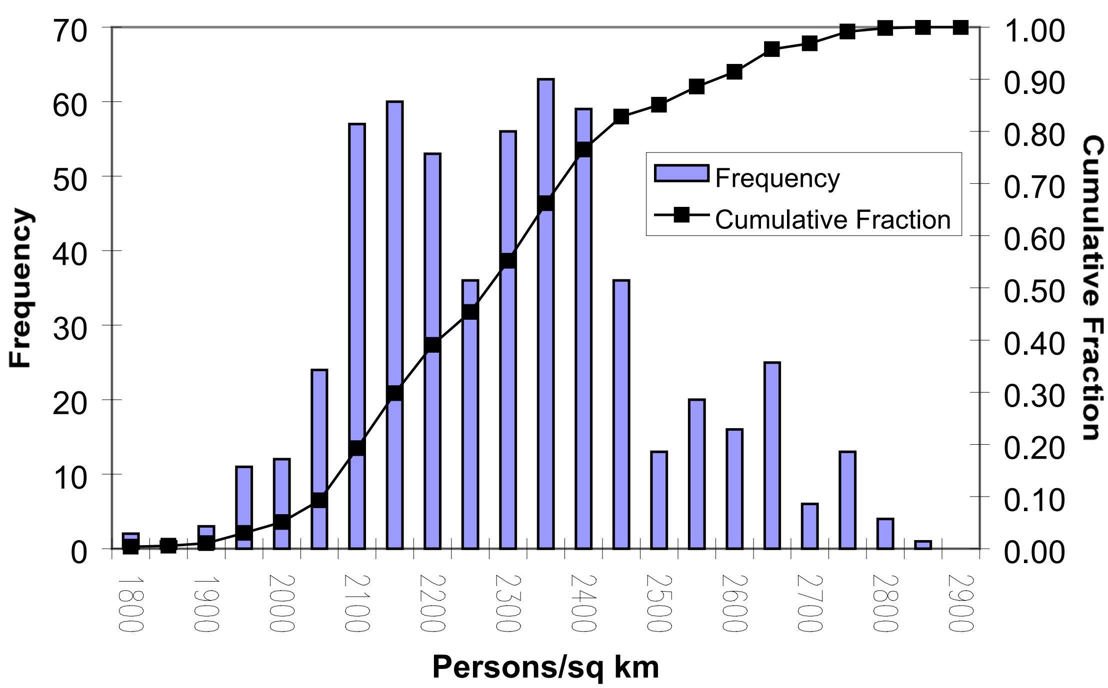

Figure 3.8a Histogram and cumulative distribution for *rural population density* for rural rail route segments.

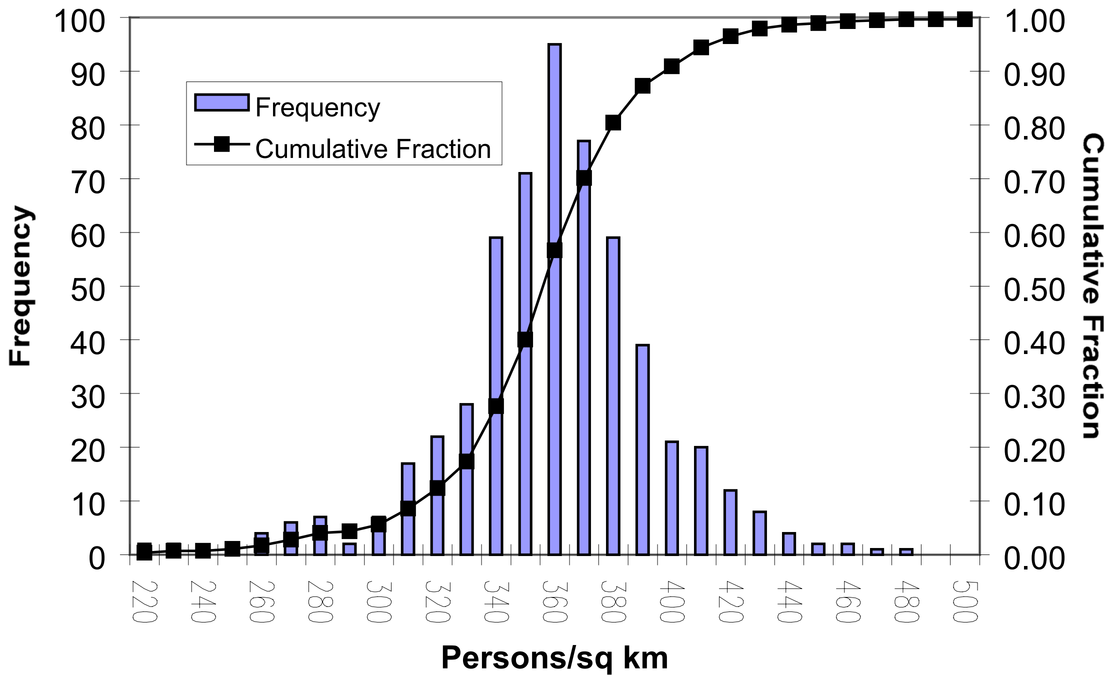

Figure 3.8b Histogram and cumulative distribution for *suburban population density* for suburban rail route segments.

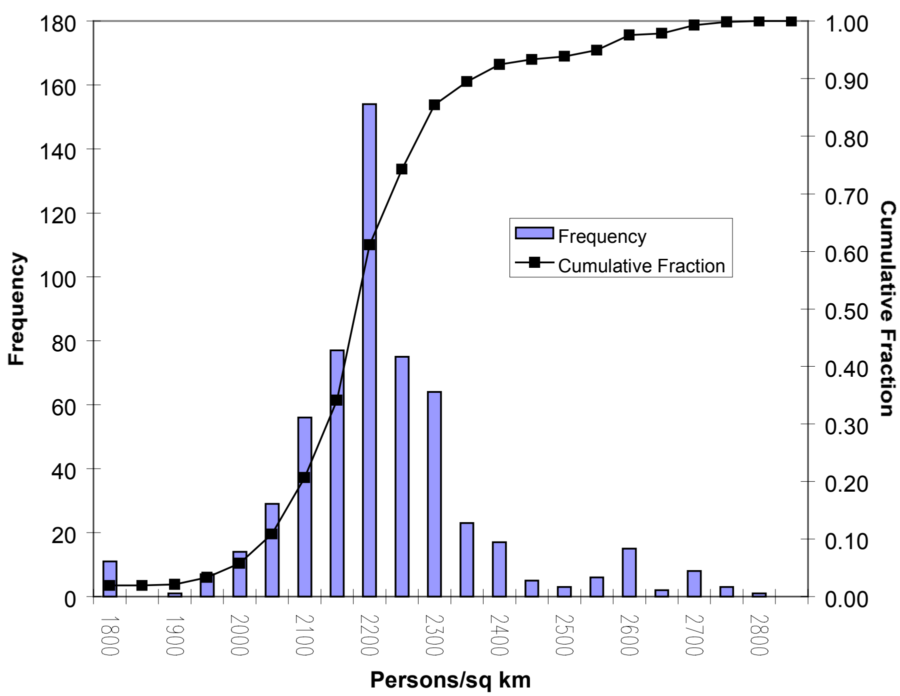

Figure 3.8c Histogram and cumulative distribution for *urban population density* for urban rail route segments.

densities from these distributions provide the necessary route-description inputs for a RADTRAN calculation. The number of sets of sampled values (and the number of RADTRAN calculations) is dependent on the number of individual parameter values to be selected by sampling, and the requirements for statistically meaningful results (at least twice the number of parameters). The size of the sample that is required to develop statistically meaningful results is discussed in Section 8.2.2

3.4.2 Truck and Train Accident Statistics

3.4.2.1 Introduction

Table 3.2 in Section 3.2 indicates that one of the More Important ("Proportional") parameters in calculating accident risks is the LINK Accident Rate. RADTRAN 5 determines the probability of an accident occurring on a particular truck- or train-route link (segment) by computing the product of its length (in kilometers) and the accident rate (number of accidents per vehicle-kilometer) for that link. In general, accident rates vary with highway or rail line classification, e.g., Interstate, U.S. and State highways, or Main and Branch rail lines. The code RADTRAN (version 1 or 5) also distinguishes between Rural, Suburban and Urban links, as defined by the population density bordering the link. For maximum specificity, distinct accident-rate values would be assigned to these distinct portions of a route as well. In reality, such detailed data are not usually available and more generalized accident rates must be used. Regulations of the DOT for truck transport of Highway Route Controlled Quantities of RAM, including spent nuclear fuel specify that Interstate highways (HM-164) be used exclusively, except where not available. Therefore, Interstate highway accident rates are of primary interest for the truck transport portion of this study.

Rail accident data available from the DOT does not identify the character (urban, suburban, or rural) of the region where the accident occurred or the population density of the accident location. However, in DOT compilations of truck accident statistics, Interstate accident rates are reported for accidents occurring in Urban and Rural areas. However, this division is not made on the basis of population density as is done for RADTRAN route segments (0 to 66, 67 to 1670, and greater than 1670 persons/km^2 for Rural, Suburban and Urban areas, respectively). Instead, the DOT division distinguishes between incorporated areas (cities) and unincorporated areas. Since there can be Suburban (or even Rural) population densities (as specified for RADTRAN) within city limits or Suburban population densities outside of city limits, the DOT division of accident statistics does not easily map into the division required by RADTRAN. Past practice has been to use the DOT Urban accident rate for Interstate highway links identified as Urban in RADTRAN and to use the DOT Rural accident rate for Interstate highway links identified as Suburban or Rural in RADTRAN. For the present study, accident rates for the entire set of routes examined, were used to construct cumulative probability distributions from which representative samples of route parameters were selected, by LHS, for use as input for RADTRAN calculations. This approach permitted an approximate separation of the tabulated DOT data into Rural, Suburban and Urban accident rates for Interstate highways, as is described in Section 3.4.2.2.

3.4.2.2 Truck Accident Data

Over the years since NUREG-0170 was published, several studies of truck accident rates were performed by the DOT, the DOE, or their contractors and the results published in formats with variable applicability to the needs of this present study. These studies are described briefly in chronological order in the following paragraphs.

Urban Study. This was an investigation of actual accident experience on city streets in an urban area (New York City) performed to answer criticisms of the single, point-estimate accident rate used in NUREG-0170. The data were gathered in the mid-1970's and the results were published in 1980 [3-18]. The accident rates obtained are not applicable to Interstate highways but are included here to indicate a potential upper limit to be reached by accident-rate distributions employed in the current study.

California Highway Department Study. Highway accident rates for three truck types and several highway types were derived from California collision reports. Data for 1980 and 1981 were extracted from individual accident files by the State of California Department of Transportation in response to a request from SNL. The results were published in a SNL report [3-28].

Modal Study. Lawrence Livermore National Laboratory (LLNL) performed an analysis of spent nuclear fuel truck transport [3-29] in which truck accident rates were derived from three sources of data: DOT Bureau of Motor Carrier Safety (BMCS, now Office of Motor Carriers), American Petroleum Institute (API), and California Department of Transportation. For the Modal Study, LLNL chose to use the API rate data because of the similarity of tanker-trucks to the trucks used to transport spent nuclear fuel casks. However, the API data included light truck accidents, which were atypical and inflated the accident rates. For this study, the BMCS accident rate data are judged to be most appropriate because the data reflects trucks and highways like those that will characterize spent fuel shipments.

SIS Project EIS. The DOE published an Environmental Impact Statement (EIS) on the Special Isotope Separation Project in which a national average accident rate for combination trucks (tractor/trailers) on Interstate highways was derived from DOT data [3-30]. Average accident rates for the specific routes considered in the EIS were also calculated and found to be nearly the same as the national average (48 states).

BMCS Data. Four years (1984 and 1986 through 1988) of accident data derived from reports submitted to the DOT by commercial carriers have been tabulated for Interstate highways inside and outside city limits (Urban and Rural by DOT definition) for each of the 48 contiguous United States. Data for 1986 through 1988 were collected in a study performed by Argonne National Laboratory (ANL Longitudinal Review) for the DOE [3-31]. BMCS data are biased (toward more severe accidents compared to total accident statistics) by the reporting criteria imposed by the DOT, but they apply most specifically to the vehicle and highway types employed in spent nuclear fuel truck shipments.

Truck accident rates and the years from which data were obtained in these various reports are presented in Table 3.6 together with the value quoted in NUREG-0170.

Table 3.6 Truck Accident Rates (Accidents per Million Vehicle-Kilometers)

Source	Period	Urban or Total Rate*	Non-Urban Rate	Comments
NUREG-0170	pre-1975	0.46		
Urban Study (NY City)	pre 1980	7.2 - 91		Depends on time of day
		15		Average
Calif. Hwy. Dept.	1980	0.8	1.1	Truck/Trailers on Freeways
	1981	0.7	1.0	Total Accidents
Modal Study				
BMCS	1960-72	1.6		Reportable Accidents
Am. Petrol. Inst.	1968-81	4.0		Used in the Study
Calif. Hwy. Dept.	1981-83	0.6		Limited Access
		3.1		4-Lane
SIS Project**	1984	0.31		Tractor-Trailers
BMCS**	1984	0.20	0.28	Interstate Highways
ANL Long. Rev.	1986-88	0.36	0.20	Interstate Highways

* Urban rate if distinguished, otherwise Urban and Non-Urban rate
** Average over 48 states

It should be noted that these values are not necessarily based on the same accident definition, truck type, highway type, or sample sizes. However, they give an indication of the range of values that pertain to different types of highways, different demographic areas, and different points in time. The data collection period was of particular concern because nearly all of these data were collected when the national speed limit, which was recently cancelled, was 55 mph.

In April of 1999, an update of the ANL Longitudinal Review was published which analyzes heavy combination truck accident data for 1994 to 1996 [3-32]. Because of changes in the way truck accident data are currently reported, the data in this report are not directly comparable with the data in the earlier ANL study [3-31]. Nevertheless, the average accident rate on Interstate highways for the three-year period for the continental United States is 3.45 accidents per 10 million truck-kilometers which is quite similar to the means of the Rural and Suburban accident-rate distributions (respectively 2.2 and 4.1 accidents per 10 million truck-kilometers) that are derived in the following paragraphs. In addition, the ANL report authors note that the accident rate on Interstate highways increased by 37% in states which increased speed limits in 1995 or 1996. The authors caution that available data do not yet establish whether this is a sustained change or a transient; in any case, it is not a large enough change to invalidate the accident-rate distributions employed in the current analysis.

The most comprehensive and recent of the data sets available at the time accident-rate distributions were developed were the BMCS accident-rate listings for all 48 states which related directly to combination truck accidents on Interstate highways. However, they were not separated into accidents within Rural, Suburban, and Urban portions of the Interstate highway system, as required for RADTRAN input; they were distinguished only according to whether accidents occurred inside incorporated areas ("Urban," referred to as City in the following discussion) or outside incorporated areas ("Rural," referred to as non-City in the following discussion). A method for separating these sets of accident-rate data into the required population-density groups, based on correlations between non-City or City accident rates with state population densities outside or inside incorporated areas (as determined by the U.S. Bureau of the Census for 1990) for each state, was developed.

For each of the 48 states, the BMCS Interstate-highway city accident rates from 1984 and the city accident rates in the ANL Longitudinal Review (1986-88), were averaged; this was also done for the non-city accident rates. In Figure 3.9a, the non-City average state accident rates that correspond to rural population densities, as defined for RADTRAN calculations (i.e., ≤ 67 persons/km^2), are plotted versus the population densities of the state's unincorporated areas (state population minus incorporated population divided by state area minus incorporated area). In Figure 3.9b, the average City accident rates for each state that correspond to suburban or urban population densities, as defined for RADTRAN calculations (i.e., > 67 persons/km^2), are plotted versus the average population densities of incorporated areas (cities with populations ≥ 25,000). This plot also contains six non-city accident rate points because they correspond to RADTRAN suburban population densities (densities greater than 67 persons/km^2). This figure also contains three points that correspond to RADTRAN urban population densities (densities greater than 1670 persons/km^2). After dropping the three urban points, histograms of the accident rates in Figures 3.9a and 3.9b were separately computed, summed, and normalized, thereby generating cumulative distributions of accident rates for accidents on Rural Interstate Highways and also on Suburban plus Urban Interstate highways in areas that have population densities that fall within the RADTRAN population density range for rural or suburban regions. These cumulative distributions are presented in Figures 3.10a and 3.10b.

These two cumulative distributions were sampled, using LHS, to provide accident-rate values for the Rural and Suburban fractions of the 200 routes in the LHS sample of More Important parameter values. Because of the lack of data for accidents in Urban areas, the three points in Figure 3.9b that have Urban densities (> 1670 persons/km^2) were averaged to provide a point-estimate accident rate of 5.2 accidents per 10^7 vehicle-kilometer for the relatively small Urban fractions of the 200 representative routes. Although less than the highest accident rate depicted in Figure 3.9b, this rate is considered reasonable for urban regions, since interstate highway speeds within the densely populated urban areas are generally lower than they are in suburban or rural regions, therefore there should be fewer reportable accidents and consequently a lower frequency of reportable accidents.

3.4.2.3 Train Accident Data

The additional sources of rail accident-rate data, that have become available since NUREG-0170 was published, are not as numerous as those for truck accident-rate data. The sets of data that were used for this study are a subset of the sources described in Section 3.4.2.2; these sets of data are listed in Table 3.7.

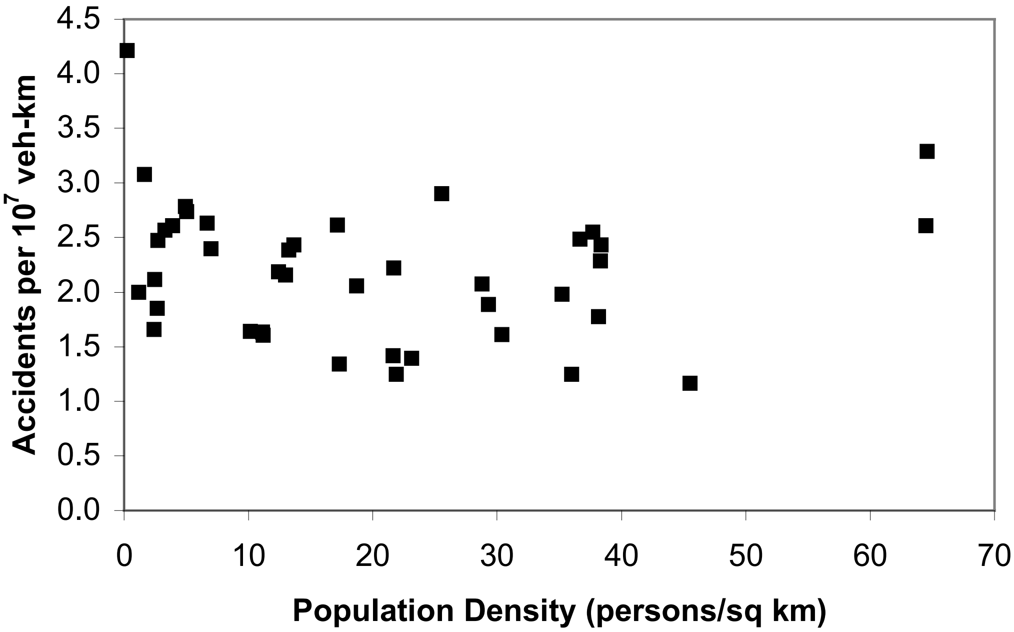

Figure 3.9a Accident rate versus rural population density.

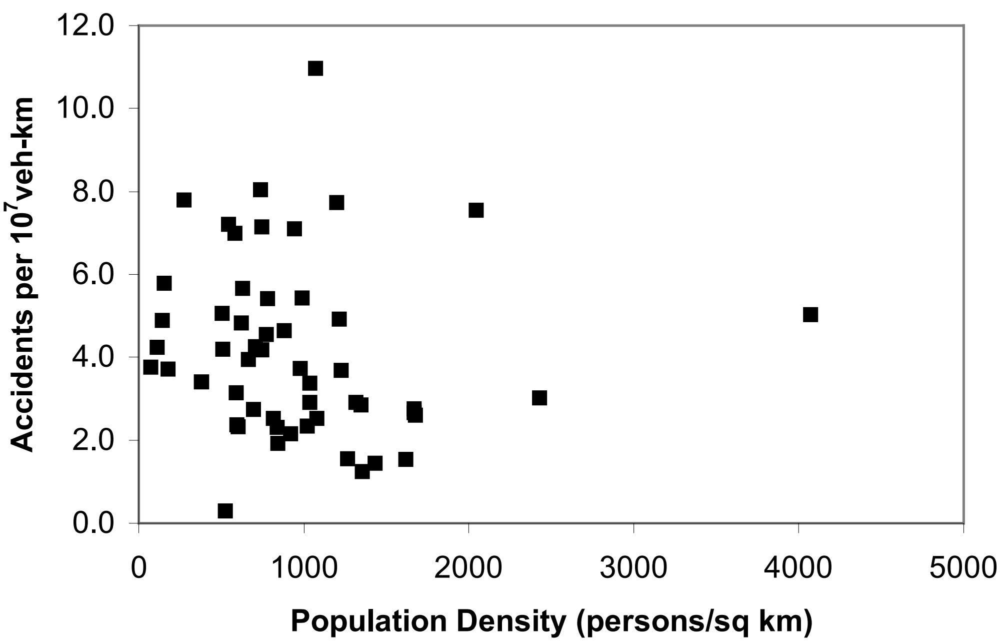

Figure 3.9b Accident rate versus suburban population density.

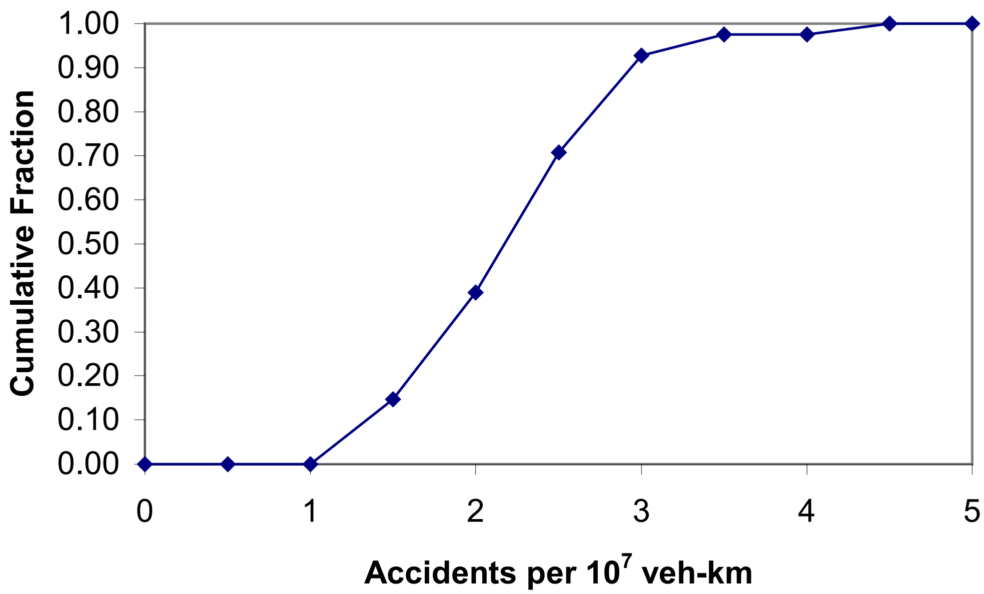

Figure 3.10a Cumulative distribution of rural accident rates.

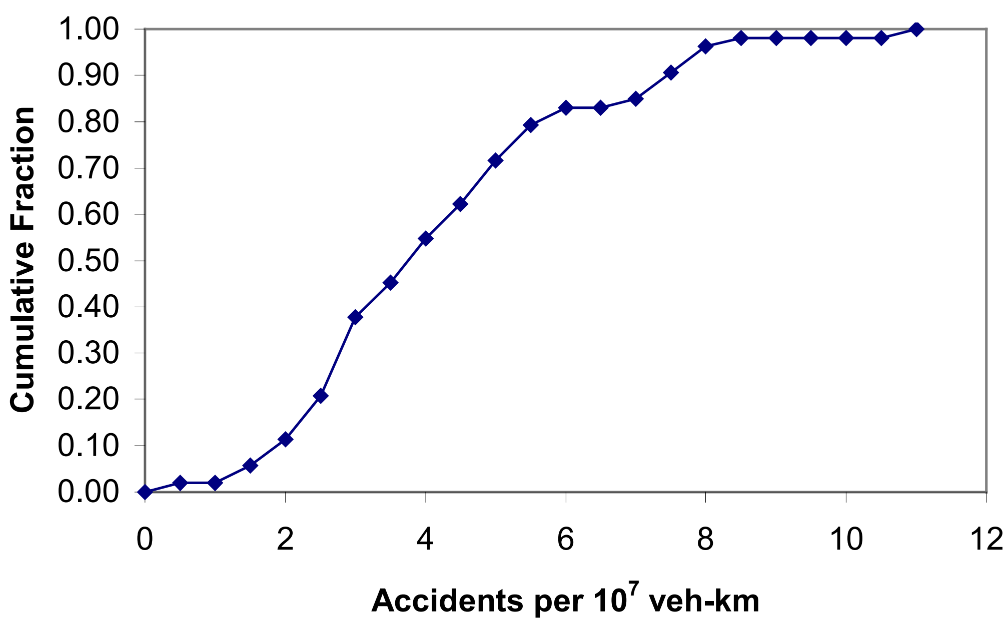

Figure 3.10b Cumulative distribution of suburban and urban accident rates.

Table 3.7 Rail Accident Rates per Million Rail Car km

Source	Date	Urban or Total*	Comments
NUREG-0170	pre-1975	0.9	Per Rail Car km
Modal Study			
Fed. Rail Admin.	1975-82	7.5 [0.11]	Per Train km, All trains & tracks Per Rail Car km @68 cars/train
ANL Long. Rev.**	1985-88	0.06	Per Rail Car km, All tracks
		0.03	Per Rail Car km, Main Line Only

* Urban rate if distinguished, otherwise Urban and Non-Urban rate
** Average over 48 states

Note that the rate from the Modal Study is per *train*-km which must be corrected to car-km for comparison to the other values. Comparing car-miles to train-miles on Class I railroads for 1980 and 1990, as obtained from the DOT Internet Web page, indicates that the approximate number of cars per train is 68. This value leads to a Modal Study accident rate of 0.11E-6 per car-km which lies between the NUREG-0170 and ANL values in Table 3.7.

A histogram and cumulative distribution of data for accidents on main lines by state, as compiled in the ANL study, were computed and the distribution is presented in Figure 3.11. The ANL study did not distinguish accidents on the basis of population densities; therefore, this distribution was sampled, using LHS, to provide accident rates for all portions of the rail routes analyzed.

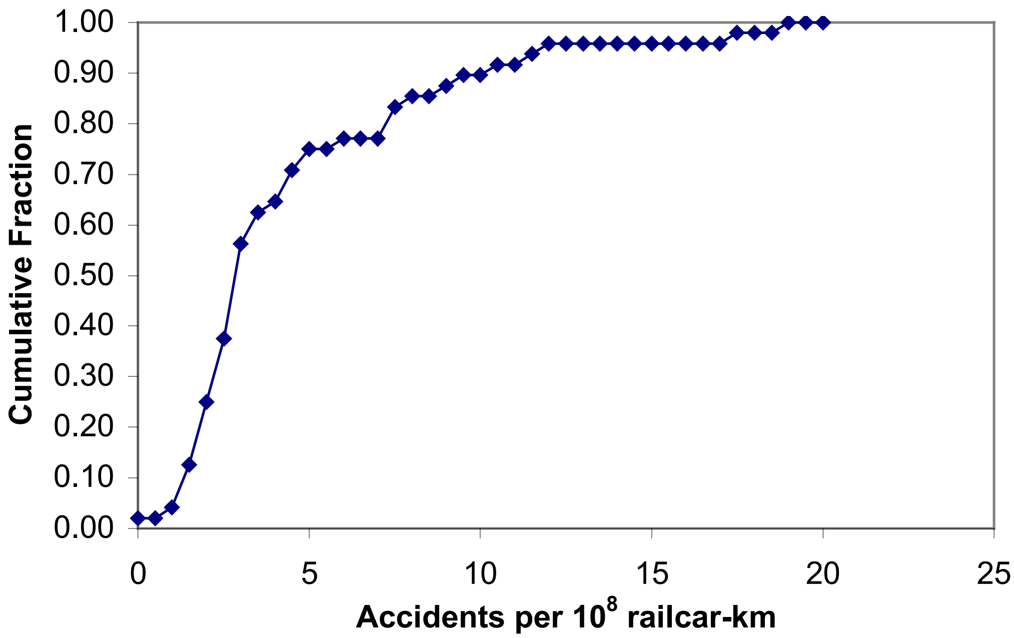

Figure 3.11 Cumulative distribution of rail accident rates (used for all segments: Rural, Suburban, and Urban).

3.4.3 Development of Miscellaneous Distributions

In addition to route parameters (length, population zone fractions, population densities and accident rates), several additional parameters were selected as suitable input for LHS. In this section, the development of distributions for the remaining LHS parameters is described.

3.4.3.1 Truck Stop Time

Fueling, eating, and other stops were characterized in a study of commercial truck stops serving a major truck transport route (Interstate 40) [3-19]. The study provided a tabulation of individual stop times (in minutes) versus number of observed stops suitable for constructing a histogram and a cumulative distribution. The results of the study were adapted to represent the totality of stops made during a typical spent nuclear fuel shipment by scaling up the observed times to values appropriate for the length of the shipment. The parameter employed in previous RADTRAN versions for estimating total stop time (0.011 hours per km of shipment length) and the average distance from the distribution of shipment distances (~1800 km) yielded an average total stop time per truck shipment of: $1800 \times 0.011 = 19.8$ hours. The individual stop times (from the study, in hours) were scaled up to yield a stop time of 20 hours at the peak of the histogram (Number of Observed Stops = 10). Table 3.8 lists the original stop times in minutes (first column), the original stop times in hours (second column), the scaled stop times in hours (third column) and the corresponding stop counts (fourth column). The cumulative distribution (fourth and fifth columns of Table 3.8) is shown in Figure 3.12; this distribution was added to the LHS input file. Note that the value of 0.011 hours of stop time per km of shipment length is descriptive of normal commercial trucking operations and includes time required by regulations for sleep.

Table 3.8 Distribution of Normal Commercial Truck Stop Times

Stop Time (min)	Stop Time (hr)	Scaled Stop Time (hr)	Number of Observed Stops	Cumulative Distribution
0	0	0	0	0
8	0.13	7	3	0.06
11	0.18	10	6	0.17
14	0.23	12	8	0.33
17	0.28	15	9	0.50
20	0.33	17	8	0.65
23	0.38	20	10	0.85
26	0.43	23	2	0.88
29	0.48	25	2	0.92
32	0.53	28	2	0.96
35	0.58	30	1	0.98
50	0.83	43	1	1.00

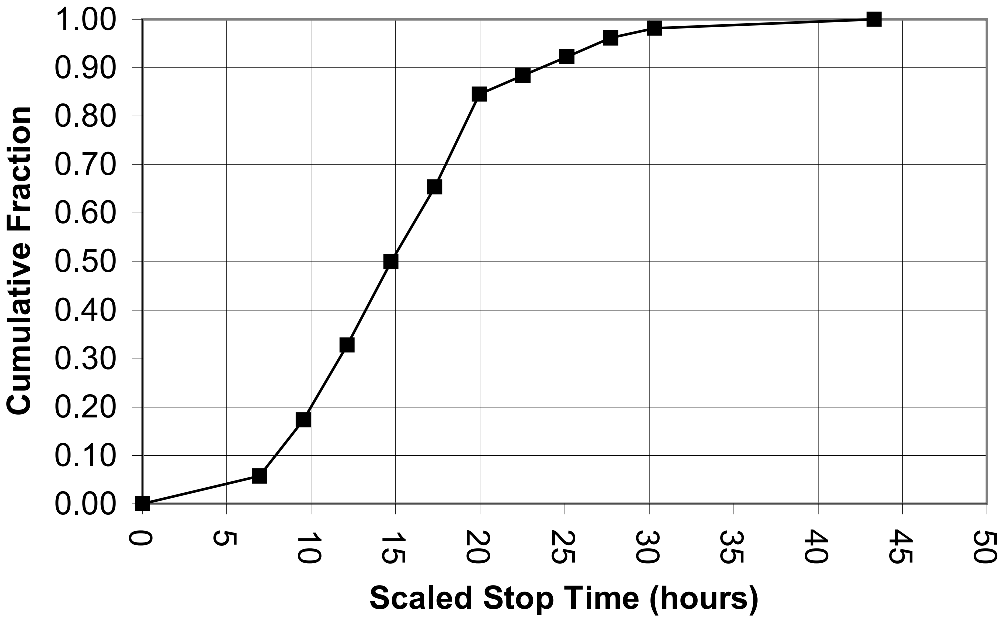

Figure 3.12 Distribution of normal commercial truck stop times.

As is discussed in Section 8.6, industry practice for spent fuel shipments under exclusive use conditions is to use two-man crews and to minimize stop time by not making stops to sleep. As is shown in Section 8.6, when spent fuel shipments are made under these special operating conditions, the incident-free risks calculated using the stop times specified by the distribution in Table 3.8 and Figure 3.12 are found to be conservative by a factor of approximately 28. In Section 8.6, this factor is used to correct by scaling the incident-free doses that are calculated using the stop time distribution presented in Table 3.8 and Figure 3.12.

3.4.3.2 Evacuation Time

The elapsed time between an accident occurrence and completed evacuation of the area around an accident site was set at 24 hours in RADTRAN I. A study of evacuation times [3-33], in which news reports of accidents requiring evacuations (e.g., transportation, refinery, and chemical plant accidents) were followed up by telephone interviews of the authorities involved in handling the accident/evacuation, provided a distribution of the times required to evacuate an accident site and the surrounding area threatened by release of hazardous materials. The data from this study were subsequently supplemented [3-34] by Department of Transportation data describing elapsed time between accidents and arrival of first-responders (Emergency Medical Service personnel) [3-35]. A histogram and cumulative distribution were constructed from the combined elapsed-time data sets. As Figure 3.13 shows, the points of the cumulative distribution are fit with high precision by a log-normal distribution. This log-normal distribution of evacuation times in days was incorporated into the LHS input files for truck and rail shipments.

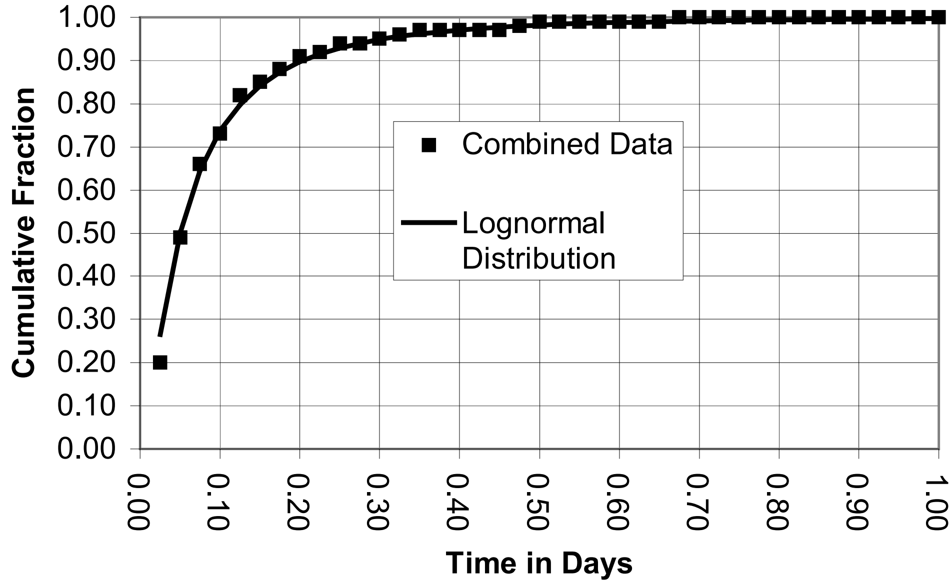

Figure 3.13 Distribution of response team arrival plus evacuation times.

3.4.3.3 Pasquill Stability Category

The relative speed of dispersion of a cloud of aerosols is related to atmospheric stability as indicated by Pasquill Stability categories A through F (in order of increasing stability). Table 3.9 presents the occurrence frequencies of these six atmospheric stability classes as calculated from national average observed stability conditions for the continental United States [3-36] and the cummulative distribution of these frequencies. This discrete cumulative distribution was used to select one of the six Pasquill atmospheric stability categories for use in each of the 200 sets of More Important parameter values selected by LHS sampling.

For risk assessment purposes, the distribution of stability class frequencies of occurrence must be very broadly based because the site of a transportation accident cannot be pre-determined nor can the atmospheric stability at a random location be reliably specified by measurements available from a distant weather station. Regional stability class occurrence statistics could be used but, for these calculations, the additional precision their use might produce was not expected to be worth the effort required to gather and process the data.

Table 3.9 Distribution of Pasquill Categories

Pasquill Category	Occurrence Frequency	Cumulative Distribution
A	0.043	0.043
B	0.190	0.233
C	0.190	0.423
D	0.216	0.639
E	0.241	0.88
F	0.120	1.00

3.4.3.4 Truck and Rail Transportation Index

Values of cask dose rates at one meter from the cask surface (RADTRAN input parameter, TI) have been calculated for truck and rail spent fuel casks by Parks et al. [3-37] for spent fuel with various cooling times. Pairing of these values, with the number of PWR and BWR assemblies in the 1994 spent fuel inventory [3-38] that have cooling times equal to the time that produced the calculated surface dose rate at 1 m from the surface, allowed cumulative distributions of cask surface dose rates to be constructed for PWR and BWR spent fuel for both truck and rail casks. Tables 3.10 and 3.11 present these distributions. Because the upper limits of these distributions were less than the regulatory limit for cask dose rates (10 mrem/hour at 2 m from the cask surface), in order to be conservative, the calculated dose rates at 1 m were scaled so that the upper limits of both distributions equaled 13 mrem/hour at 1 m, which for a cask with a maximum dimension of 5 meters is equivalent to the regulatory cask dose rate limit. Finally, because the difference between the PWR and BWR distributions was insignificant compared to the expected accuracy of the model, a single distribution of TI values was constructed by pooling the truck cask or rail cask PWR and the BWR data. These distributions are presented in the last column of Tables 3.10 and 3.11.

Table 3.10 Distribution of Dose Rate at 1 m (RADTRAN parameter TI) for Truck Casks

Cooling Time (yr)	TI	BWR		PWR		Distribution Used in Calculations
		Assys. of that Age	Cumulative Distribution	Assys. of that Age	Cumulative Distribution	
5	**13.0**	3781	1.000	2824	1.00	**1.00**
10	**6.39**	3832	0.725	2785	0.711	**0.72**
15	**4.57**	2735	0.447	1937	0.427	**0.44**
20	**3.49**	2131	0.248	1662	0.229	**0.24**
25	**2.76**	1290	0.094	575	0.059	**0.08**

Table 3.11 Distribution of Dose Rate at 1 m (RADTRAN parameter TI) for Rail Casks

Cooling Time (yr)	TI	BWR		PWR		Distribution Used in Calculations
		Assys. of that Age	Cumulative Distribution	Assys. of that Age	Cumulative Distribution	
3	**13.0**	1900	1.000	1400	1.000	**1.00**
5	**6.72**	3781	0.879	2824	0.875	**0.87**
10	**3.95**	3832	0.637	2785	0.622	**0.63**
15	**3.03**	2735	0.393	1937	0.373	**0.38**
20	**2.43**	2131	0.218	1662	0.200	**0.21**
25	**1.99**	1290	0.082	575	0.051	**0.08**

3.4.3.5 Highway Traffic Density

Traffic density information is used in calculating On-LINK incident-free doses in RADTRAN 5. Distributions of this parameter (in units of vehicles per hour per lane) for rural and suburban areas were developed from Department of Transportation publications tabulating miles of rural interstate highway together with vehicle-miles per year for each state [3-39] and daily freeway traffic per lane for 377 urbanized areas [3-40], respectively. For the rural distribution, the annual vehicle-miles value for each state was converted to vehicles per hour (dividing by the state's miles of interstate and the number of hours per year). The value of vehicles per hour per lane (as required by RADTRAN) was approximated by assuming that rural interstate highways typically have two lanes in each direction. These values were used to construct the histogram and cumulative distribution shown in Figure 3.14. The data for urbanized areas included population density for each area. In an effort to separate the data into suburban and urban groups, the traffic densities were plotted versus their respective population densities (Figure 3.15). Nearly all of the data points lie in the suburban range (67 to 1670 persons/km^2); the points within the range were used to construct the suburban traffic density histogram and cumulative distribution shown in Figure 3.16. The 200 values of rural and suburban truck traffic density incorporated into the 200 sets of More Important parameter values were selected from these distributions using LHS sampling methods.

Because there were so few points in the urban population density range (> 1670 persons/km^2), the value of the largest traffic density, 930 vehicles per hour per lane, was assumed to be a conservative point-estimate for urban portions of the truck shipment routes.

3.4.3.6 Persons per Vehicle Sharing a Highway Route

Persons per vehicle data are used in RADTRAN 5 to calculate On-LINK incident-free doses. A tabulation of private vehicle occupancy in the United States for 1990 [3-41] derived from the 1990 Census of Population by the Journey-to-Work and Migration Statistics Branch, Population Division, U.S. Bureau of the Census was converted to a discrete cumulative distribution for LHS input (Table 3.12). Because the original tabulation did not distinguish vehicle occupancy according to population density, the same distribution was used in the LHS input for rural, suburban, and urban portions of the truck shipment routes.

Table 3.12 Distribution of Persons per Vehicle on Highway Routes

Persons per Vehicle	Fraction of Vehicles	Cumulative Distribution
1	0.846	0.846
2	0.121	0.967
3	0.02	0.987
4	0.007	0.994
5	0.002	0.996
6	0.001	0.997
>6	0.003	1

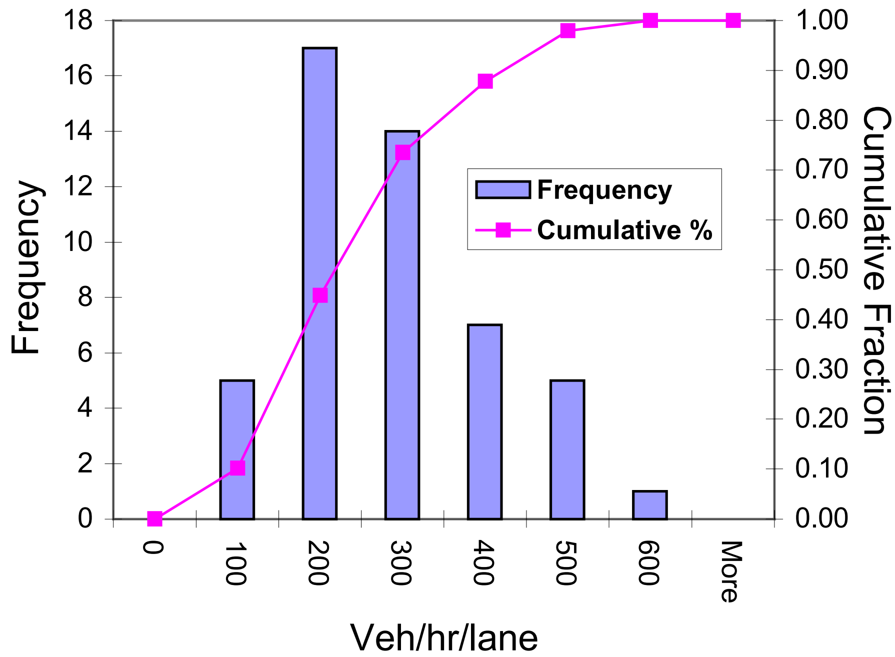

Figure 3.14 Histogram and cumulative distribution of rural interstate traffic density.

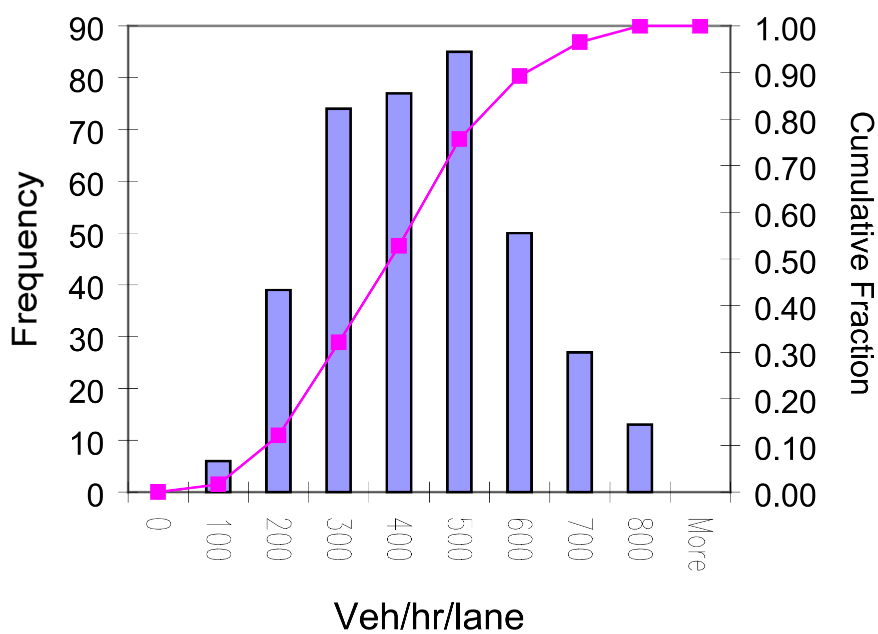

Figure 3.15 Histogram and cumulative distribution of interstate traffic density for urbanized areas

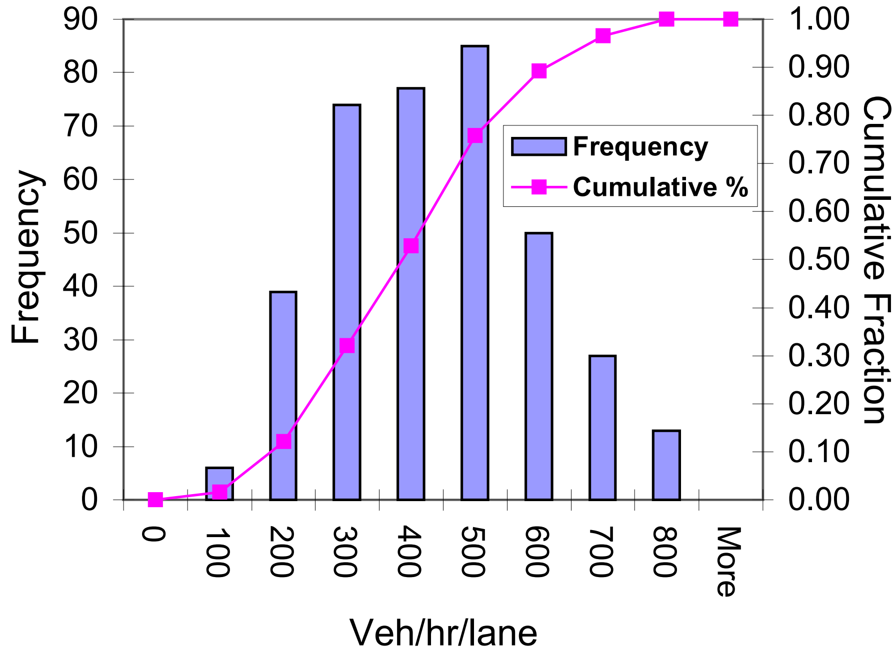

Figure 3.16 Histogram and cumulative distribution of suburban interstate traffic density.

3.5 References

[3-1] K. S. Neuhauser and F. L. Kanipe, "RADTRAN 5, Technical Manual," Sandia National Laboratories, Albuquerque, NM (in preparation, draft available on request).

[3-2] K. S. Neuhauser and F. L. Kanipe, "RADTRAN 5, User Guide," Sandia National Laboratories, Albuquerque, NM (draft available on the RADTRAN web site).

[3-3] G. S. Mills and K. S. Neuhauser, "Sensitivity Analysis for RADTRAN 4 Input Parameters," 88th Annual Meeting of the Air & Waste Management Association, San Antonio, TX, 1995.

[3-4] G. S. Mills, K. S. Neuhauser, and F. L. Kanipe, "Application of Latin Hypercube Sampling to RADTRAN 4 Truck Accident-Risk Sensitivity Analysis," Proceedings of PATRAM '95, Las Vegas, NV, 1995.

[3-5] G. S. Mills, K. S. Neuhauser, and F. L. Kanipe, "RADTRAN 4 Truck Accident Risk Sensitivity Analysis," Proceedings of Waste Management 95, WM Symposia, Tucson, AZ, 1995a.

[3-6] A. G. Croff, "ORIGEN2 - A Revised and Updated Version of the Oak Ridge Isotope Generation and Depletion Code," ORNL-5621, Oak Ridge National Laboratory, Oak Ridge, TN, July 1980.

[3-7] G. D. Wyss and K. H. Jorgensen, “A User’s Guide to LHS: Sandia’s Latin Hypercube Sampling Software,” SAND98-0210, Sandia National Laboratories, Albuquerque, NM, 1998.

[3-8] U.S. Nuclear Regulatory Commission, “Reactor Safety Study,” WASH-1400, Washington, DC, 1975.

[3-9] M. L. Abbott and A. S. Rood, “COMIDA: A Radionuclide Food-Chain Model for Acute Fallout Deposition,” EGG-GEO-10367, Idaho National Engineering Laboratory, Idaho Falls, ID, 1994.

[3-10] M. M. Madsen, and E. L. Wilmot, “Truck Transportation of Radioactive Materials,” Proceedings of the 7th International Conference on the Packaging and Transportation of Radioactive Materials (PATRAM ‘83), Vol. I, p. 724, New Orleans, LA, 1983.

[3-11] R. M. Ostmeyer, “A Revised Rail-Stop Exposure Model for Incident-Free Transport of Nuclear Waste,” SAND85-1722, Sandia National Laboratories, Albuquerque, NM, 1986.

[3-12] K. S. Neuhauser and R. F. Weiner, “Intermodal Transfer of Spent Fuel,” Proceedings of the 10th International Conference on the Packaging and Transportation of Radioactive Materials (PATRAM ’92), Vol. I, p. 427, Yokohama, Japan, 1992.

[3-13] H. S. Javitz, et al., “Transport of Radioactive Material in the United States: Results of a Survey to Determine the Magnitude and Characteristics of Domestic, Unclassified Shipments of Radioactive Materials,” SAND84-7174, Sandia National Laboratories, Albuquerque, NM, 1985.

[3-14] K. F. Eckerman and J. C. Ryman, Federal Guidance Report No. 12, “External Exposure to Radionuclides in Air, Water, and Soil,” Oak Ridge National Laboratory, Oak Ridge, TN, 1993.

[3-15] R. J. Engelman, “Effectiveness of Sheltering in Buildings and Vehicles for Plutonium,” DOE/EH-0159T, U.S. Department of Energy, Washington, DC, 1990.

[3-16] J. M. Taylor and S. L. Daniel, “RADTRAN II: Revised Computer Code to Analyze Transportation of Radioactive Materials,” SAND80-1943, Sandia National Laboratories, Albuquerque, NM, 1982.

[3-17] Waste Isolation Pilot Plant Disposal Phase Final Supplemental Environmental Impact Statement, Volume II Appendices, DOE/EIS-0026-S-2, U.S. Department of Energy, Carlsbad, NM, 1997.

[3-18] N. Finley, et al., “Transportation of Radionuclides in Urban Environs: Draft Environmental Impact Assessment,” Volumes 1 and 2, NUREG/CR-4829, Nuclear Regulatory Commission, Washington, DC, 1980.

[3-19] N. R. Griego, J. D. Smith, and K. S. Neuhauser, "Investigation of RADTRAN Stop Model Input Parameters for Truck Stops," Conference Proceedings, Waste Management 96, Tucson, AZ, 1996.

[3-20] County and City Data Book, 1988, U. S. Department of Commerce, Washington DC, 1988.

[3-21] J. D. Smith, K. S. Neuhauser, and F. L. Kanipe, "Expected Residence Time Model," Conference Proceedings, Waste Management '96, Tucson, AZ, 1996.

[3-22] U.S. Environmental Protection Agency, Proposed Guidance on Dose Limits for Persons Exposed to Transuranic Elements in the General Environment, EPA-520/4-77-016, U.S. Environmental Protection Agency, Washington, D.C., 1977.

[3-23] D. Chanin and W. B. Murfin, "Site Restoration: Estimation of Attributable Costs from Plutonium-Dispersal Accidents," SAND96-0957, Sandia National Laboratories, Albuquerque, NM, 1996.

[3-24] International Council on Radiation Protection, "Limits on Intakes of Radionuclides by Workers, Parts 1-3," Annals of the International Council on Radiation Protection, Vol. 2 (3-4), 1979 through Vol. 8 (1-3), 1982), Pergamon Press, Oxford, England, 1979.

[3-25] P. E. Johnson, et al., "HIGHWAY 3.1 – An Enhanced Highway Routing Model: Program Description, Methodology, and Revised User's Manual," ORNL/TM-12124, Oak Ridge National Laboratory, Oak Ridge, TN, 1993.

[3-26] P. E. Johnson, et al., "INTERLINE 5.0 – An Expanded Railroad Routing Model: Program Description, Methodology, and Revised User's Manual," ORNL/TM-12090, Oak Ridge National Laboratory, Oak Ridge, TN, 1993.

[3-27] J. W. Cashwell, et al., "Transportation Impacts of the Commercial Radioactive Waste Management Program," SAND85-2715, Sandia National Laboratories, Albuquerque, NM, April 1986.

[3-28] R. N. Smith and E. L. Wilmot, "Truck Accident and Fatality Rates Calculated from California Highway Accident Statistics for 1980 and 1981," SAND82-7066, Sandia National Laboratories, Albuquerque, NM, 1982.

[3-29] L. E. Fischer, et al., "Shipping Container Response to Severe Highway and Railway Accident Conditions," NUREG/CR-4829 UCID-20733, Lawrence Livermore National Laboratory, Livermore, CA, 1987.

[3-30] U.S. Department of Energy, "Final Environmental Impact Statement on Special Isotope Separation Project," DOE/EIS-0136, U.S. DOE, Washington, DC, 1988.

[3-31] C. Saricks and T. K. Kvitek, "Longitudinal Review of State-Level Accident Statistics for Carriers of Interstate Freight," ANL/ESD/TM-68, Argonne National Laboratory, Argonne, IL, 1994.

[3-32] C. L. Saricks and M. M. Tompkins, "State-Level Accident Rates of Surface Freight Transportation, A Reexamination," ANL/ESD/TM-150, Argonne National Laboratory, Argonne, IL, 1999.

[3-33] G. S. Mills, et al., "Study of Evacuation Times Based on General Accident History," Proceedings of the 11th International PATRAM Conference, Las Vegas, NV, 1995.

[3-34] G. S. Mills, et al., "Study of the Components of Evacuation Times," Proceedings of the 12th International PATRAM Conference, Paris, France, 1998.

[3-35] "1992 Traffic Safety Facts Annual Report," U.S. Department of Transportation, Bureau of Transportation Statistics, BTS-CD-04-01.

[3-36] D. Bruce Turner, "Workbook of Atmospheric Dispersion Estimates," PHS Publ. No. 999-AP-26, U.S. Department of Health, 1969.

[3-37] C. V. Parks, et al., "Parametric Study of Radiation Dose Rates from Rail and Truck Spent Fuel Transport Casks," ORNL/CSD/TM-227, 1985.

[3-38] "Spent Nuclear Fuel Discharges from U.S. Reactors," Energy Information Administration, U.S. Department of Energy, SR/CNEAF/96-01, 1994.

[3-39] Federal Highway Administration, Combination of Tables HM-50 and VM-2 in Section V of "Highway Statistics for 1997" derived from the Highway Performance Monitoring System, U.S. Department of Transportation Web site.

[3-40] Federal Highway Administration, Table HM-72 in Section V of "Highway Statistics for 1997" derived from the Highway Performance Monitoring System, U.S. Department of Transportation Web site.

[3-41] www.census.gov/population/socdemo/journey/usveh90.txt.

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